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DEVELOPMENT OF A STABLE ULTRAVIOLET SOURCE

AND TECHNIQUES FOR ACCURATE RADIOMETRY

Annual Summary Report

January 1, 1965 - December 31, 1965

by

Henry J. Kostkowski
Charles R. Yokley
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Albert T. Hattenburg

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NBS

U.S. DEPARTMENT OF COMMERCE

NATIONAL BUREAU OF STANDARDS

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NATIONAL BUREAU OF STANDARDS REPORT

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Development of a Stable Ultraviolet Source and Techniques for Accurate Radiometry

High Pressure Arc Source

A small portable model of the high pressure plasma arc described in last year's report has been developed and tested. This source is very promising as a stable source of high radiance, particularly below 3000 Å. At 2500 Å typical radiance temperatures vary from 5000 °K to 7500 °K depending on the mode of operation, and the spectral radiance has a reproducibility of a few percent.

Part I of this report contains a description of the characteristics of this source and the required associated equipment. Detailed drawings of some of the critical components, mechanical and electrical, are also provided.

A more accurate determination of spectral radiance and a determination of the optimum manner in which the arc should be used and calibrated is still required. Also the possibility of using the arc as an ultraviolet irradiance standard should be investigated. These studies are being considered for the near future.

High Accuracy Spectral Radiance Calibrations

The spectral calibration of tungsten strip lamps in terms of absolute watts per steradian per unit prejected area per wavelength interval from 8500 Å to 2100 Å can now be performed with an estimated (95% confidence) uncertainty of about 1% to 3% respectively. The uncertainty relative to the International Practical Temperature Scale is somewhat less, about 2/3 of the above values.

A report of the philosophy, approach, results, and limitations of this work is presented in Part II. This is essentially a lecture presented by the principle investigator at a radiometry course at Eppley Laboratories and brought up to date for this report. Until reprints of the research paper on this work are available, the modified course notes is the best report available.

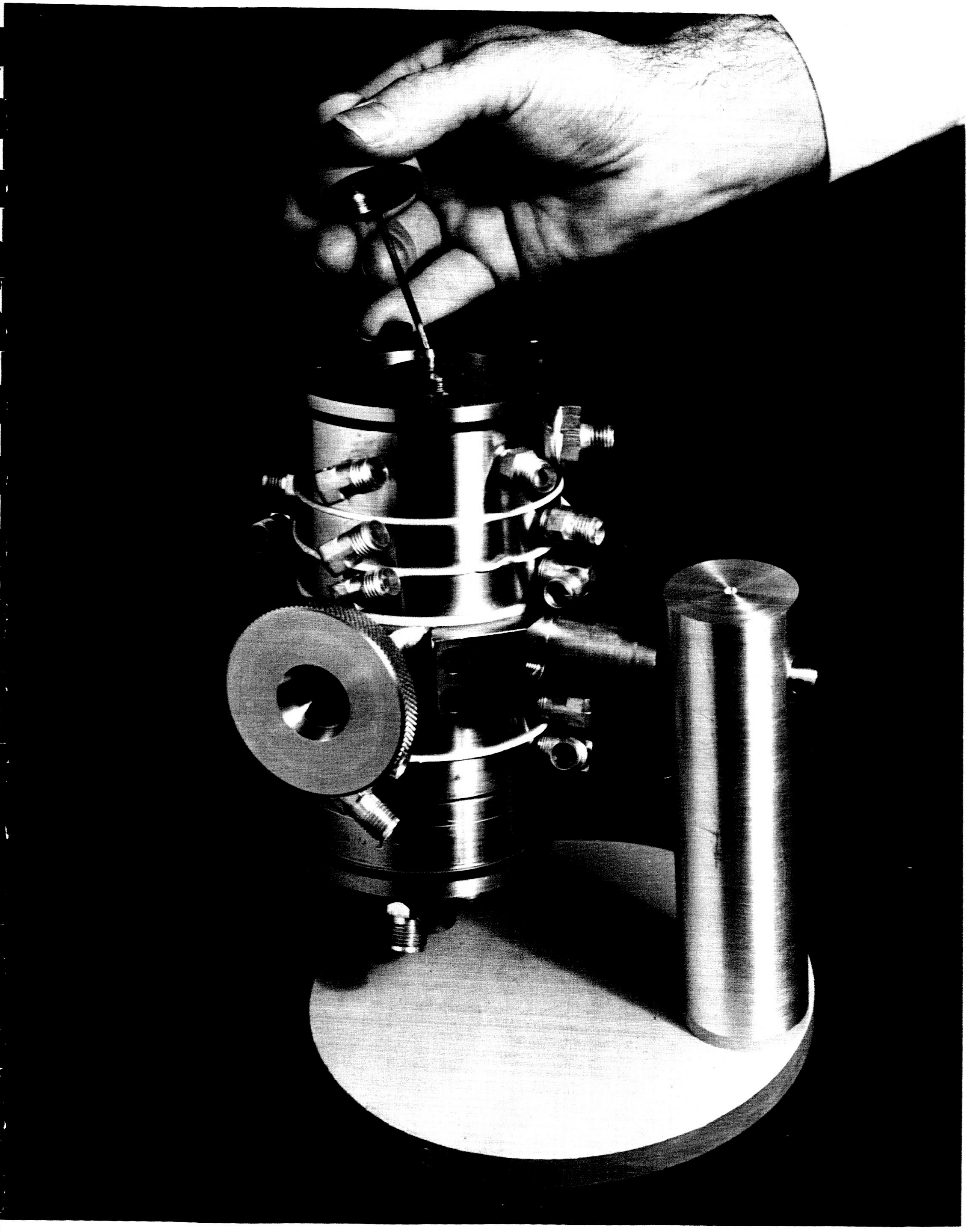
Low Current Graphite Arc

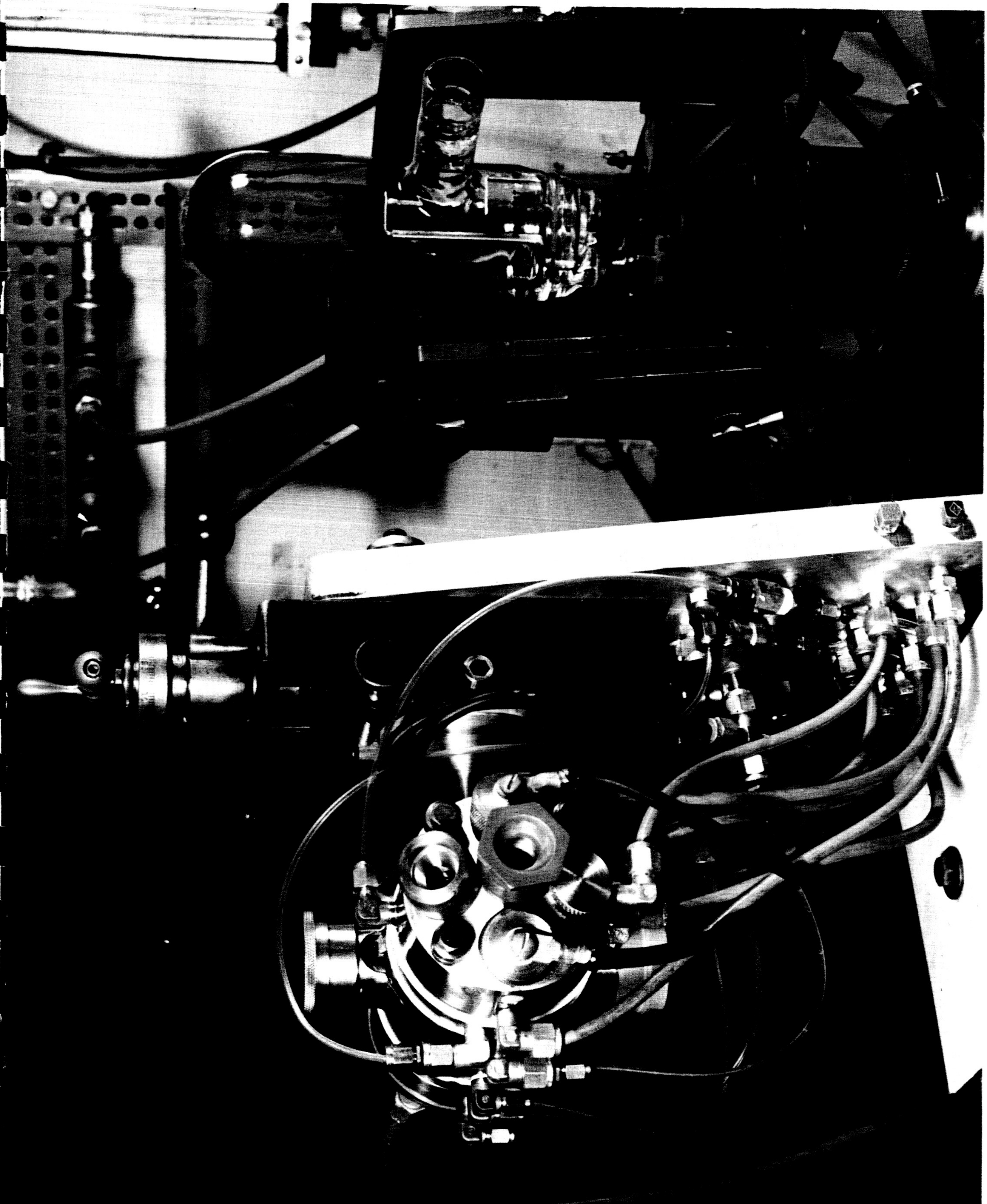
The spectral radiance of the positive crater of a low current graphite arc has been determined at wavelengths from 8500 Å to 2100 Å for which the arc is a useful standard. The arc has an uncertainty about three times greater than a tungsten strip lamp which has received a high accuracy calibration at NBS, is less convenient to use, and cannot be used where the band spectra is strong. On the other hand, the arc's spectral radiance is 10, 100, and 2,000 times that of a strip lamp at 8500, 2800 and 2100 Å respectively, the initial capital investment is less, and the arc need not be calibrated or recalibrated periodically as do strip lamps. The details and results of the arc measurements are reported in Part III.

PART I

HIGH PRESSURE ARC SOURCE

C. R. Yokley





INTRODUCTION

The essential goals of the contract proposal have been met and a small arc-type source for use in the ultraviolet has been designed, constructed, and partially tested. Depending upon the mode of operation, the ultraviolet radiation from the source has a radiance temperature from 5000 °K to 7500 °K, and operation is continuous. With the exception of one line at 2478 A, the radiation in the 2000 A to 3350 A range appears to be a continuum when observed with a spectral band pass of 0.85 A. The radiation output exhibits low noise, approximately 1/2% or less when observed with a system having a three second time constant.

The useful range of the source extends over a wide wavelength region from the vacuum ultraviolet to about 4000 A, where the spectral radiance approaches that of a carbon arc (3800 °K). The 4000 A limit can be extended by using the arc end-on as shown in Fig. A-11. The spectral radiance is relatively constant from 3000 A to 5000 A and exhibits a weak maximum at about 4000 A.

The reproducibility in spectral radiance is such that calibrations (within a few days) may be repeated to within 3% (standard deviation) over the wavelength range 2200 A to 3100 A. One set of measurements made at one wavelength indicates that the standard deviation of the spectral radiance may be reduced to 1% for situations in which precise source alignment is possible.

The external appearance of the arc-source is shown in the photographs. In the first photograph, the unit is assembled for use in a side-on mode. The tungsten cathode is shown being inserted into the operating position. When the source is assembled for end-on use the appearance is as given in the second photograph. The last photograph shows an exploded view of the arc parts. The size of the arc is seen to be comparable to that of a laboratory strip lamp reference source.

Description of the System

1. The Arc Chamber

The arc-source is essentially a wall-stabilized arc in which the currents and pressures used are such that the arc fills the channel through which it passes. Thus the volume of radiating gas is both made spatially stable and raised to high power densities by nature of the dimensions involved. Based on an effective arc diameter equal to the radiation half-width (ultraviolet) of the arc, the electrical input power in the side-on observation zone ranges from 90 to 350 KW per cm^3.

The actual radiation characteristics of arc-sources such as this depend upon the energy-level distribution of the gas used. The excitation is derived from heating due to the arc current and serves to populate the upper energy levels and the continuum. The resultant transitions to lower levels produce the observed radiation.

Argon is an economical, readily available gas that performs well in this arc. The discharge is stable and operating voltages are fairly low (70 to 100 volts). Although argon is used exclusively for the experiments to be discussed, other gases may be used in the observation zone while still providing a protective atmosphere of argon around the electrodes.

The amount of radiation that can be collected from a gaseous source depends upon the volume of gas contributing. In arcs of the nature to be described, it has been found that the geometric stability for high pressure (300 psi) is best for about 1/8" channel diameter and for plate spacings not exceeding .084". If a small zone within the arc is selected for observation there will be a solid angle beyond which the internal parts of the source become limiting aperature stops. The f/-number* for this source is the order of f/7 for the internal parts, and f/4.4 for the arc window. The useful

*In this report f/-number is defined to be the ratio of the distance of a point source from the limiting parts to the diameter or spacing of these parts.

portion of the quartz window on the strip lamp reference has an f/-number of 4.4. In practice, the limiting stop for all measurements is chosen smaller (f/25) so as to make alignment less critical.

The design of the arc-source is essentially that of the prototype (1). Significant changes have been made in the size and weight of the assembly, and the source itself can be considered portable. An exploded view of the arc used for side-on measurements is given in the third photograph. The individual elements from left to right are the anode, 1st constriction, 2nd constriction, center mount and window assembly, 3rd constriction, 4th constriction and the hollow cathode. The details of the individual units are given in the appendix, Figs. A-1 to A-7.

The cathode has been designed with a 1/8" diameter central hole which admits a brass starting rod. The arc is ignited by quickly lowering and withdrawing the rod after the power has been turned on. Initially, the open circuit voltage is about 300 V. If power supplies having outputs much lower than this are used, the arc becomes quite difficult to start. After igniting, the voltage drops to the operating range of about 90 V.

The actual cathode to which the arc finally becomes attached is a 5/32"D tungsten rod approximately 4" long. The rod is held by a small collet in the sealing-cap which clamps the rod about 3 1/4 inches from the point of arc attachment.

The arc chamber is sealed by lowering the 5/32" 1% thorium cathode down the central hole and screwing the cap to which it is attached down against an O-ring. Internally, the 5/32" cathode projects about .050" from its holder and extends to within about .050" of the 4th constriction. After sealing, the arc current and pressure are set to the required values. For applications where very small solid angles can be tolerated, the cathode rod can be omitted and a quartz window installed in the sealing cap. The f/-number thus obtained is about f/32 based on a point source at the center of the arc.

2. Ancillary Hardware

Stable operation of such an arc-source requires a current regulated d.c. power supply, a water cooling system, an argon metering, and a pressure measuring and regulating system and a reproducible mounting base for optical alignment. The individual characteristics of each system are summarized in the appendix (Table A-1). Once set up, use of the source becomes easily routine. It is merely necessary to turn the power and cooling water on, strike the arc (as described above), and adjust the pressure and current to the required values.

3. The cooling system.

The stabilizing walls for the arc are constructed for forced convection cooling with high velocity water. Each constriction unit is fitted with a small copper insert with internal baffles as shown in figures A-6 and A-7 in the appendix. All units are connected to the water supply in parallel for the higher currents. The system is used without recirculation or special water treatment and no failures have been noted which were cuased by poor heat transfer due to internal scale.

4. Argon Flow System

The argon supply to the arc is regulated at two levels. Tank pressure is reduced to 600 psi in a preliminary manifold and then to the arc by a second regulator. The flow in the system is regulated by four constriction values individually connected near the anode and cathode and between the 1st and 2nd and the 3rd and 4th constrictions.

The individual flow rates are a matter of an empirical choice but have certain ranges within which the arc is spatially stable. The arc stability is most sensitive to flow at high pressure and these flow rate settings are determined for the actual pressures and currents to be used and kept constant thereafter.

The most critical flows are those in the ends of the arc near the cathode and anode and tangential injection of argon gas into these zones is used. The flow values are tabulated in Table A-2 of the appendix, but in general terms the total rate of argon amounts to about 60% of a tank per day of operation (130 ft^3). The actual effect of flow on the values of the spectral radiance for such arcs will be described below. In a calibration, the gas flow is fixed as well as the operating current and pressure.

5. Power Supply

The power to the arc source is delivered at constant current. The details of the series regulator current control have been described elsewhere [1]. The current regulation (±.05 amp) is such that the effect in terms of uncertainty in the spectral radiance due to current is about 0.2%.

The series unit has also been incorporated in the design of a portable power supply (size limitation is the 30 KVA isolating transformer) and a schematic of the connections are shown in Fig. A-8.

In the original reference [1] the power input was initially direct current (650V) but contained about 12V (p-p) of 360 cycle ripple and the regulator was required to operate as an active filter as well. Three phase full-wave rectification has more ripple than the regulator could handle (18V p-p), and a separate active filter is used to reduce the input ripple to about 4V pp. This is well within the capcity of the current regulator and results in a final ripple in arc current of 0.2% at the 30 amp level for

300 volt input. The arc source requires a no load voltage in the order of 250 volts minimum for easy starting, and the operating voltage is between 70V and 100V. Most of the excess voltage appears across the cathode balancing resistors (R_k) which are about 7 ohms each. This is the lowest value of balance resistance tested for which the cathode current divides evenly and remains ignited simultaneously on both electrodes.

In many cases where arc-sources are to be used, existing power arrangements can be adapted with a considerable economy in hardware. When the voltages are sufficiently high, adjustable series ballast resistors [2] can be used to regulate the arc current. Two arc power systems used at NBS use batteries (100 AH, 6V) in banks of 200V which may be operated in combination to provide 200, 300 or 600 volts at currents to 100 amperes.

Current Measurement

For a given geometrical configuration of the arc stabilizing parts, the spectral radiance is primarily dependent upon the magnitude of the arc current. In the case of the end-on arc the currents used range from 30 to 75 amperes, and the relationship is nearly linear as shown in Fig. A-13. The slope over the range is .088 spectral radiance units per ampere. At the 50 ampere level, the current must be known to better than ±.1 amp for a ±.3% uncertainty in spectral radiance. This accuracy falls in the range of potentiometric current measurements. The current sensing shunt is connected in the power loop as shown in Fig. A-8 in the appendix and is fairly close to ground potential.

When arcs such as these are being powered from sources containing some ripple, corrections have to be made in order to repeat spectral radiance data obtained for pure direct current. If the peak-to-peak ripple is less than one-half percent, usually the corrections are negligible relative to the experimental errors in spectral radiance.

Source Alignment

The measured radiation emitted from arc-type sources involves the individual contribution of all of the emitters within the effective solid angle limited by the optics. Inasmuch as large temperature gradients exist in such arcs (3) the optical alignment becomes critical. Adjustments for scanning as well as reproducing translations along the x, y and z (Fig. A-11) coordinates must be available. Rotations relative to the horizontal and vertical axes are also required. The sensitivity of any one adjustment is dependent on the size of the target area and the homogeniety of the emitting volume. The sensitivity in the measurement of spectral radiance as obtained with the equipment used amounts to about a 1% uncertainty when the individual deviations for each degree of freedom are added for worst case.

The most sensitive motion for the side-on arc is along the x-axis where a displacement of the target area of .005" results in a 1% lowering in the observed spectral radiance.

Alignment of the measuring instrumentation with the true axis of the end-on arc is the most difficult of all adjustments. This critical alignment is a rotation and requires vernier controls. Rotation of .2 radians swings the output signal through the entire range. A summary of the alignment characteristics is given in Table A-3 in the appendix.

6. Factors affecting Spectral Radiance of Arc-type Sources.

The spectral radiance of the arc-source is determined by measuring the ratio between the arc and a well known reference source. The reference used for these experiments was a quartz-window tungsten strip filament lamp and was especially calibrated for use in the 2100 A to 3391 A ultraviolet range. The special ultraviolet calibration was performed in another part of the Radiation Thermometry Section by direct comparison of the lamp (at constant current) to a high-temperature, high-quality blackbody. The method eliminates the need for tungsten emissivity data at the respective operating temperature and the spectral transmittances of the quartz window.

A scan across a typical tungsten strip lamp shows a change in the spectral radiance of about 2% per millimeter when examined with a .2mm square test area in the vicinity of the strip center. A similar comparison for the arc-source shows a spectral radiance change of about 50% per millimeter. In the case of the side-on arc, the change in spectral radiance is due to both the temperature profile and the change in depth of the observed volume of gas.

The measurement is made spectral through the use of a small .5 meter Ebert Spectrometer. The optical arrangement is given in Fig. [A-9]. The necessary focusing and folding of the optical path is done with uncoated front surface aluminized mirrors. At the short wavelengths the intensity is limited by the quartz window in the arc chamber and the sapphire window on the photomultiplier. The effect of scattered light in the spectrometer is reduced to about 2% of the signal down to 2400 A by the characteristics of the photomultiplier. The EMR541F used has a long wavelength cut off of about 3600 A and is referred to as a "solar blind" multiplier.

The scattered light in the measured radiation from 2100 A to 2400 A was estimated by inserting band-pass filters which cut off at wavelengths slightly longer than the one in question. The zero signal for all measurements both arc-source and strip lamp were verified by use of suitable test filters as described above. Actually, the scattered light corrections are necessary only for the strip lamp calibration. The arc has a spectral distribution which minimizes the scattered light in the ultraviolet, and the dark current signal and scattered light test signal are nearly identical.

It was pointed out above that the actual value of observed spectral radiance for non-homogenious sources depends on the "zone" in the source selected by the optical arrangement of the measuring system. All measurements reported here are for a target area .023" high and .013" wide. These dimensions amount to 27% and 17% of the arc half-width respectively. Additionally, an external circular stop established the limiting aperature for arc-source and reference alike and had a nominal value of f/25 for side-on observations. The alignment relative to the x-axis is determined by searching for the peak radiation signal. Vertical settings are determined by optically determining the optical axis midway between the upper and lower constriction plates. Once this reference datum has been established, the rotations are "tuned" for maximum radiation signal.

There is a slight variation of intensity in the vertical direction (y axis) in the arc space between the constriction plates for side-on observations of the arc. Fig. [A-10] gives the results of a vertical scan through the geometrical center of the arc for a very small test zone (.05 x .08 at f/300). The half-height width is very close to the mechanical measurement of the plate spacing. The wing detail arises from reflections from the constricting plates at each end of the scan.

A horizontal scan (X-Axis) through the vertical midpoint between the constricting plates is given in Fig. [A-10]. The half-width depends upon the pressure, current and flow conditions, but is nominally 1.7 mm or 54% of the arc channel diameter. The range of half-widths observed over all test conditions varies from 1.6 mm to 1.9 mm.

A considerable amount of care must be exercised in translating back and forth between the arc-source and the reference strip lamp. All translations are measured with dial-gage stops and reproduced to .001".

The alignment of the strip lamp relative to the filament notch and envelope arrow provided for that purpose is accomplished by placing strong light at the exit slit and adjusting the focus, tilt, and rotation relative to the optical axis established by the beam.

Since there were no requirements for line shape determinations, wide slits were used. The band pass of the measuring instrumentation is about 17 A.

Windows and absorbing media in the optical path.

The short wavelength cut off of ultraviolet light from the arc source is determined by the window. Both quartz (1850 A grade) and LiF (1350A) windows have been used, but the bulk of the work has been done with quartz. The windows are seated in a sleeve-type holder and can be easily removed for cleaning, substitution, or testing. When the arc is being observed side-on, there are two windows 180° apart and the rear window has 10° slanted surfaces to eliminate reflection problems when the data for temperature profile studies are being taken.

There has been no observed trend in the spectral radiance measurements that would indicate changes in window transmittance as a function of ultraviolet irradiation. Measurement made after long exposure (16 hrs) are just as apt to be lower or higher than the original measurement.

An aluminum film filter is used in the system to reduce the intensity of the arc before entrance into the spectrograph. The choice of the value of filter transmittance is a compromise between that required to allow the use of a constant photomultiplier voltage, a maximum anode current of 5×10^{-8} amperes, and values of measured photo-currents that fall within the range of the available electronic attenuation.

It was found that the fatigue effects of the phototube could be minimized by using a program of exposure to high photo-current prior to the actual measurements. A "pre-fatigue" current of about 2×10^{-7} amp for a period of forty minutes stabilizes the tube so that the fatigue effects are negligible. Actually, if the tube is left dark for an extended period, some regain is observed (3% or so) but the original current is repeated if the time the tube is re-exposed is equal to twice the dark time.

The filter used was evaporated on a quartz substrate and used in the 2000 A to 3200 A range. The transmittance is not neutral but varies from about 1% at 2100 A to 1/2% at 3100 A. The arc source itself is suitable for calibration of the ultraviolet filter as it has the necessary intensity as well as stability for the procedure. The filter calibration is carried out using the same spectrograph slits and external optics as are to be used with the actual measurements of the arc and strip lamp. The measured radiation drift during the time required for the measurement is not detectible. The attenuation of the filter is the ratio of the photo-currents with and without the filter in the optical path. The illuminated area of the filter was about a 1.5 cm diameter area and the mounting system permitted precise replacement of the filter relative to the calibrated area with respect to tilt, translation and rotation. All the measurements were verified for alignment by testing for the peak value of the radiation signal. The maximum photocurrent was limited to 1×10^{-7} amperes.

Throughout the range of pressures and currents investigated, argon arcs of this nature are still optically thin. An estimate of the emissivity is made possible by the temperature profile experiments and will be discussed later. Additional radiation power may be obtained by arc designs permitting observation through long path lengths providing that the excited gas in the path is spatially stable. The result of such an arrangement is more radiation for the same electrical power input.

This arc may be used in either of two modes that is side-on or end-on. Fig. A-11 shows schematically the general arrangement for both cases. When the arc is being observed side-on, relatively short path lengths are involved. The arc is symmetrical about the vertical axis and a scan from the 1% to 1% edge intensity of the arc is typically 4 mm for constriction plates (C_2,C_3) with 1/8" holes. As mentioned the width of the half intensity points is nominally 1.7 mm. Only one cathode is used when the system is set up for side-on use.

The arc zone generally used is in the center of the assembly as indicated and the separation from the electrodes enchances the local spatial stability. The total volume of excited gas based on the width of the arc out to the 1% radiation values in the observation zone is very small (.08 cm^3) and corresponds to an average power density of about 60 kw/cm^3 for a 50 ampere arc.

Observation of the radiation along the entire long axis of the arc is obtained by fitting the arc assembly with a special split cathode as shown schematically in F g. A-11. Two small 1/8" tungsten electrodes each carry half the arc current and extend to within .050" of the 4th constriction plate. These electrodes do not project into the solid angle described by the optical system and cannot be "seen" by the measuring instrumentation. The pertinent details of the split cathode holder and the electrode configuration itself is given in Fig. A-5 in the appendix. The end-on exit beam calculates to f/5.4 for a point source at the center of the arc and is determined by the hole diameter of the last constriction plate. The beam passes through a removable quartz window which permits a similar starting procedure as used with the side-on assembly.

Geometrical Factors:

The Dependence of Spectral Radiance Upon Plate Spacing.

When arc-sources are being considered as reference sources various questions arise concerning the dependence of the measured spectral radiance upon the geometrical configuration of the stabilizing elements. The stability in this arc depends primarily on the separation of the constricting plates (free arc length) and the diameter of the holes through which the arc passes. The constriction plate hole diameter has been set at 1/8" for this source and the dependence of spectral radiance upon plate spacing will be discussed below.

The spectral radiance for the side-on source was measured for 14 increments of plate spacing at constant wavelength, current and pressure. The spacings were measured optically after each reassembly of the source by vertically scanning the source with very narrow beam optics (f/300, target .05 mm x .08 mm). Each measurement was made at the respective operating pressure and current. The spacing range is from .053" to .084" which is about the limit for geometrically stable arcs of this design.

A least squares fit to the data shows the trend over the range (Fig. 1). The target area used corresponds to the radiation peak signal along the x-axis and the mid-position between the constricting plates in the vertical direction.

The conclusion is that the dependence is rather mild, and over the total range of plate spacing amounts to only a 3% change in spectral radiance. Interpreted in terms of probable assembly limits (.005") for a source of this design, an uncertainty of about 1% in spectral radiance or 4 deg in radiance temperature is expected due to spacing error for the worst case.

During the plate spacing experiments, measurements were also made of the half-width of the arc in order to determine the amount of bulging of the free arc. A straight line was fitted (least squares) to the data and provides a relationship between the spectral radiance and the radiation half-width and indicates that the "narrow" arcs have the highest spectral radiance. The relationship between the arc radiation half-width and the spectral radiance 2800 A at constant current and pressure is given in Table I. The data are for a side-on 15 atm., 50 amp arc when the target area (.013" x .023") is centered between the constricting plates and adjusted for the maximum measured radiation signal along the x-axis (Fig. 11).

TABLE I

Arc Half-Width (mm)	Relative Spectral Radiance
1.55	1.000
1.66	.954
1.72	.908
1.75	.885
1.77	.870
1.80	.847

An implication is that such a relationship may be used to normalize the behavior of other arcs being used in the field. The procedure would be to apply a correction factor determined from the actual arc half-width to the base value for fixed specification of pressure and current.

The necessity of such a correlation was emphasized by the performance of a second arc-source from randomly selected parts. The unit was tested under identical conditions specified for the original unit including the original window. Even though all of the externally controlled operating parameters were verified as being exactly the same, the measurement of spectral radiance was 14% higher than that of the first unit. It is felt that for these reasons that no arc-type assembly of this design could be built and operated according to specification to better than about 14% without recourse to the above mentioned normalization technique.

Generic Behavior of the Arc-Source

When the data for three geometrically similar arcs are compared for the same operating current and pressure a feeling as to the class behavior of such arc sources is obtained. In this case, the prototype and two of the portable arcs were compared at 50 ampere currents and 15 atmos. pressure (Fig. 7). The range in spectral radiance for these three arc-sources was ±13% of the mean. The associated range in radiance temperature is ±1 1/4%. The range in the observed performance may be considered as characteristic of uncalibrated sources of this design when the current, pressure and flow are maintained at prescribed values. The only geometrical restriction is that the arc constriction plates have hole diameters and separations of .125" and .070" respectively. Unfortunately, the half-widths of the prototype were not measured and the normalization technique mentioned above could not be tested.

The Dependence of Spectral Radiance Upon Arc Current and Pressure

The magnitude of arc-source spectral radiance depends upon the actual wavelength, the operating current and pressure, and to some extent the flow rates used. For a given arc assembly the flow rates in terms of exit gas flow are fixed. The dependence upon current and pressure is given in Table 2 and in Fig. A-14 in the appendix.

TABLE 2

Wavelength	dN/dP*	
(microns)	50 Amp	75 Amp
0.21	913	1750
.25	3600	6340
.31	4950	9550
.4229	5310	9930
.53	4040	7210
.56	3980	6770
.6546	2710	4720

*dN/dP has units of watt cm^{-2} cm^{-1} $ster^{-1}$ psi^{-1}.

The result is that for the 50 amp 300 psia arcs, a 3 psi (1%) pressure change reflects as a 0.6% change in spectral radiance at 2500 A. The pressure regulating system maintains the set point to within ±1/2 psi which, if left unadjusted, contributes a ±0.1% uncertainty in spectral-radiance.

The sensitivity of the spectral radiance to small changes in current at constant wavelength is shown in Fig. A-13 in the appendix. The dependence is nearly linear over the range and amounts to 3.2% per ampere. Since the current is controlled to .05 ampere, the uncertainty in spectral radiance due to current drift is about 0.2% when left unattended. Data for the individual measurements are taken only when the current and pressure values are at the set point.

<u>Further Characteristics of the Arc:</u> Radial Temperature Profiles and Electron Density.

Side-on measurement of the energy emitted from such arc-type sources involves the individual contribution of all radiating atoms in the optical path. The radial characteristics of the arc (plasma) may be obtained from the side-on data using various analytical techniques [4]. The transformation from side-on data to the radial information is known as the Abel integral equation. In these experiments, an analog computer [5] was used for most of the measurements. A check was made of the analog results through use of a digital recording scheme [6] with subsequent computer computation of the data.

Electron density and temperature profiles have been made on both the prototype arc-source and the portable model. In all cases to be mentioned, the arc constricting plates have 1/8" diameter holes. The current and pressure conditions are as recorded on the curves. The temperatures measured were based on line intensity measurements as determined from the corrected area under the lines. The system was calibrated through the use of a standard strip-lamp reference source. Generally, area measurements extended to about 7 line half-widths either side of the line center. The calculations are based upon the method described by Drellishak, Knopp and Cambel [7] which were incorporated into tables of reference data (extended to 100 Atm) by Shumaker [6]. The tables relate the particle and electron density for various argon lines to the system pressure and temperature. The results for several currents and pressures are given in figures [2,3] and in Table 3.

TABLE 3

50 Amp. 15 Atmos., 4300A AI, Analog Abel

	Radius (cm)				
	0	.0516	.0693	.0924	.115
Particle Density	2.71×10^{13}	2.51	2.14	1.92	1.55
Electron Density	2.5×10^{17}	2.4	2.2	2.0	1.75
Temp(°K)	11,750	11700	11550	11450	11250
Half Width (A)	4.94	4.35	4.20	3.94	3.53

75 Amp. 15 Atmos., 4300A AI, Analog Abel

Particle Density	2.8×10^{13}	2.77	2.68	2.50	2.25
Temp(°K)	11,950	11,900	11,875	11,750	11,600

There is substantial agreement in the electron density measurements for either digital or analog computation from the arc center out to about 0.6 mm beyond which the digital computation gives consistantly lower electron densities. Additionally, for radii greater than about .6 mm, there is disparity not only in the results between the two Abel methods used, but also between the line half-width and the electron density. The net effect is that the temperatures in the outer zones of the arc remain too high. This anomaly has been observed by others as well*, and as yet no explanation has been found.

An approximation for the spectral emissivity of the heated argon in the arc can be made by assuming an average temperature of 11,500 °K (Fig. 4) over the target area of the measured radiation for the 50 amp, 20 atmosphere arc. The ratio of the spectral radiance of the arc (Fig. 6) at 2800 A and 4200 A to that of a 11,500 °K blackbody is .002 and .005 respectively and the arc can be considered optically thin.

Results

The information discussed so far has been for the purpose of describing the geometric character of such arc-sources in relation to the spectral radiance. As pointed out, the measurement of radiant energy is more critical with gaseous sources in depth than with solids primarily due to the significantly larger temperature gradients. However, once the target area location has been defined, the reproducibility in spectral radiance makes the application of such a source attractive.

A calibration of such a source involves the specification of the spectral radiance in a particular zone in the arc when the current, pressure, and flow is fixed. The calibration may be repeated in the field by reproducing all of these values. As yet, no mathematical relationship has been derived to relate all of the variables to spectral radiance, and therefore calibration curves published by N.B.S. for specific operating conditions should be used. A typical calibration curve is given in Fig. 5.

The reproducibility in spectral radiance for the prototype arc has been determined from 2200 A to 7000 A fig. 6, and averages to about 2.5% (standard

*Private communication J. C. Morris, AVCO Corp., Wilmington, Mass.

deviation) over this range. Reproducibility as used in this report is defined as the standard deviation of the measurements of the ratio of the spectral radiance of the arc-source to that of the strip-lamp reference source. The portable arc has not been tested over as wide a range, but shows a reproducibility of 2.4% in the range of 2200 A to 3000 A. The reproducibility may be somewhat better than this as a standard deviation of 1% was observed for a set 13 measurements at a single wavelength (2800 A) during which the optical alignment and arc plate spacing was not disturbed.

The generic behavior of arcs of this design is shown in Fig. 7 where both the prototype and portable arc characteristics are plotted. Data for the second assembly of the portable arc was measured at 2800 A only. If the data for the single measurement of the #2 assembly of the portable arc is ignored, then a data spread of ±6% could be expected in the spectral radiance in the performance of two similar arcs operated at the same current and pressure. The comparison is not rigorous however, in that neither the flow rates nor the plate spacing were exactly the same. If the deviation of the #2 assembly is considered to be characteristic over the wavelength range given, then the limits must be widened to ±12% to include all the data. Unfortunately, the arc half-widths had not been measured for the prototype, and the normalization technique could not be tested. Additionally, the generic comparison is based on a rather long term basis (months), and any change in the strip-lamp radiance would be reflected in the comparison data. Since the data for the prototype fell consistantly below that of the newer design the arc half-width was probably wider resulting in a lower average power density.

Spectral Radiance: The End-On Arc

The end-on arc is 21 times as long as the half-width of the side-on arc and the increase in spectral radiance is a factor of 29 for the same current and pressure. The increase is rather substantial and permits use of the arc at high spectral radiance values (radiance temperatures to 7500 K) or at reduced power for the same spectral radiance. A 5 atmos. arc operated at 30 amp produces a radiance temperature in the ultraviolet of approximately 6000 °K which is about the same as that of the sun. This arc was evaluated in the ultraviolet range of 2200 A to 3100 A from a reproducibility point of view by comparison to the strip-lamp mentioned above and the results are presented in Table 4.

TABLE 4

Wavelength (microns)	Spectral Radiance (watt $cm^{-2}cm^{-1}ster.$)	Standard Deviation (%)
0.22	4.75×10^6	5.8
.23	6.33	5.4
.24	7.99	3.3
.25	8.61	3.7
.26	8.67	2.2
.27	8.99	2.2
.28	9.39	2.1
.29	9.73	2.5
.30	10.1	2.2
.31	10.9	2.4
	Average......	3.2

In the range from 2600 A to 3100 A, the reproducibility is about the same as for the side-on arc but is significantly worse for the shorter wavelengths. The data is calculated from three individual runs with system shut down between each run.

Conclusion

The results show that arc-sources of the type described, when operated according to a particular format for the controlled variables mentioned, may be used as sources of ultraviolet spectral radiance where reproducibility in the order of 3% is acceptable. Available radiance temperatures range from 5000 °K to 7500 °K depending upon the pressure, current and mode of observation. Comparison data for the range of spectral radiance exhibited by the arc is given in Fig. 8.

In all applications of such a source where the spectral radiance is to be either measured or used the values are valid for specific target areas and for specific solid angles associated with such an area.

Strong continuum radiation from such arcs extends throughout the spectrum from 2000 A to 8000 A. The spectral radiance is not significantly greater than that of the carbon arc (3800 °K) at wavelengths greater than about 4000 A for side-on arcs. This limit is moved further to the red when the arc is used end-on. The relative spectral radiance increase, is about a factor of 30 for the 5 atmosphere 50 ampere arc.

With the exception of the 2478 carbon line the radiation from 2000 A to 3350 A appears to be a continuum. The carbon line is probably due to thermal decomposition of organic material from the electrical insulating gaskets and the plastic lines used for gas connections. Considerable line spectrum is observed in the 4000 A to 4400 A range and the lines observed are shown in Fig. A-12. The results for scans at three pressures are superimposed and are indicative of the rising continuum with pressure.

The 30 amp, 5 atmosphere end-on arc appears promising but lacks reproducibility at the shorter wavelength end of the region studied. Otherwise, this arc exhibits good stability and reproducibility in addition to high spectral radiance (6000 °K).

Spectral radiance data collected on arcs of this design indicates that if a similar arc were constructed in any machine shop in the field and operated according to the format laid out above, that the resultant spectral radiance would not be closer than about a 10% deviation from the nominal value. If however, a correction factor is used which is based upon the observed half-width of the field unit and an empirically determined equation obtained at NBS, it is probable that the uncertainty in spectral radiance could be reduced.

Cost Analysis

During the year, two arc-sources and a number of spare parts were manufactured in the Bureau shops. The total cost for about 2 1/2 units was $8,000., and the cost per unit is estimated at 0.32 man-years or about $2,900. Additional equipment for a complete system involves, for the most part, power supply components, regulators, valves flow meters, and a precision pressure gage and raises the total cost to about $5,300. In laboratories where a suitable power supply is already available (300V, 30A, .2% ripple and .2% stability) about $1,500 may be deducted from the total. Some inquiries have been made relative to a commercially available power supply and no unit appears to be available which has all of the necessary requirements. One manufacturer produces an all solid state unit which might be applicable, but would still have to be modified to regulate for constant current. The cost of the commercial unit is about $5,500. For those interested in building this radiation source, a complete set of working drawings can be made available.

Acknowledgement

The author is indebted to Dr. J. B. Shumaker for a great deal of assistance relative to the radial temperature measurement experiments and to Dr. H. J. Kostkowski for his over-all assistance in matters pertaining to the radiometric part of the program.

A significant aid to the analysis of the temperature profiles was a set of tables computed by Dr. Shumaker which relate the argon plasma composition to the temperature and pressure over the range of 5000 °K to 20,000 °K and 1.0 atmosphere to 100 atmospheres respectively.

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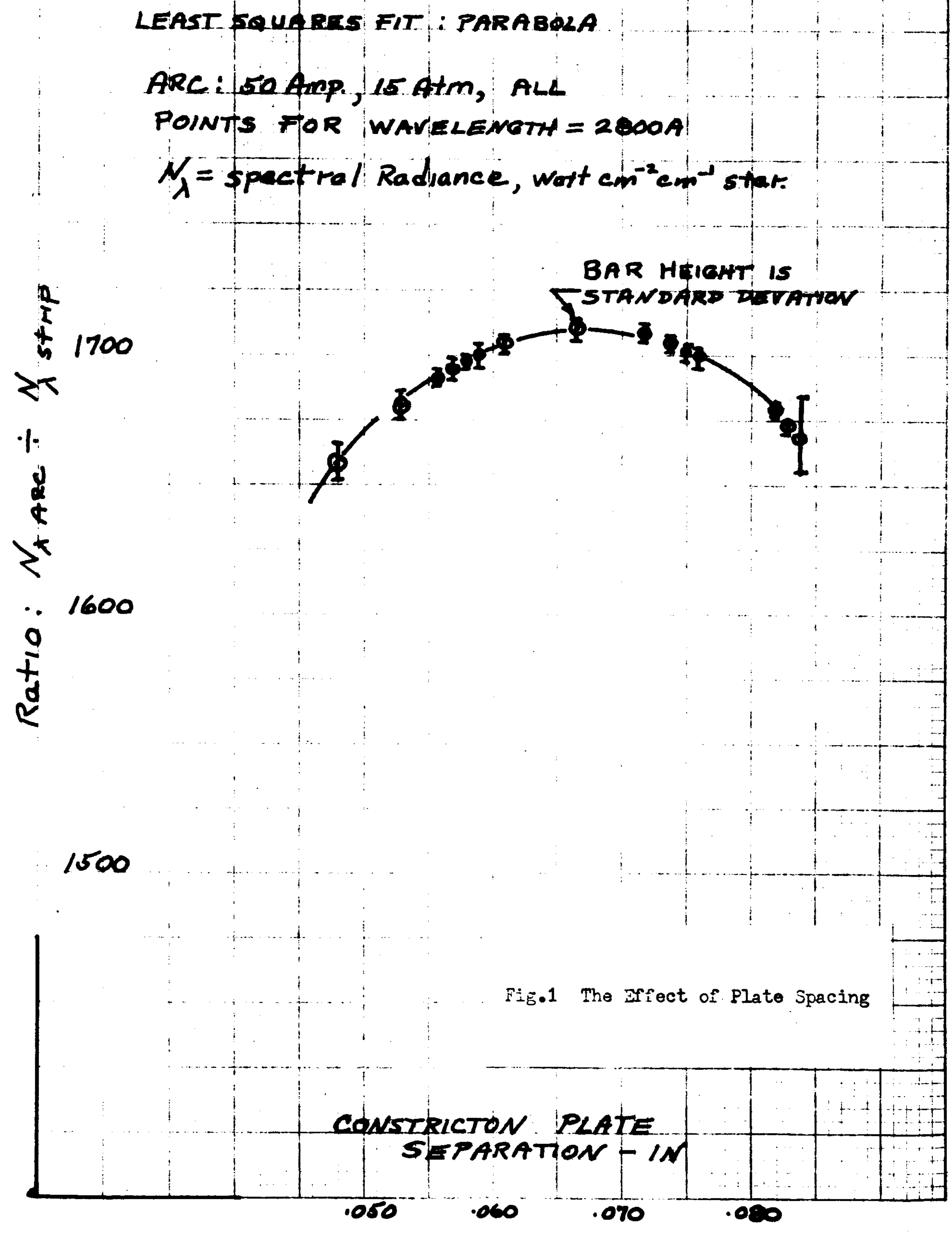


Fig.1 The Effect of Plate Spacing

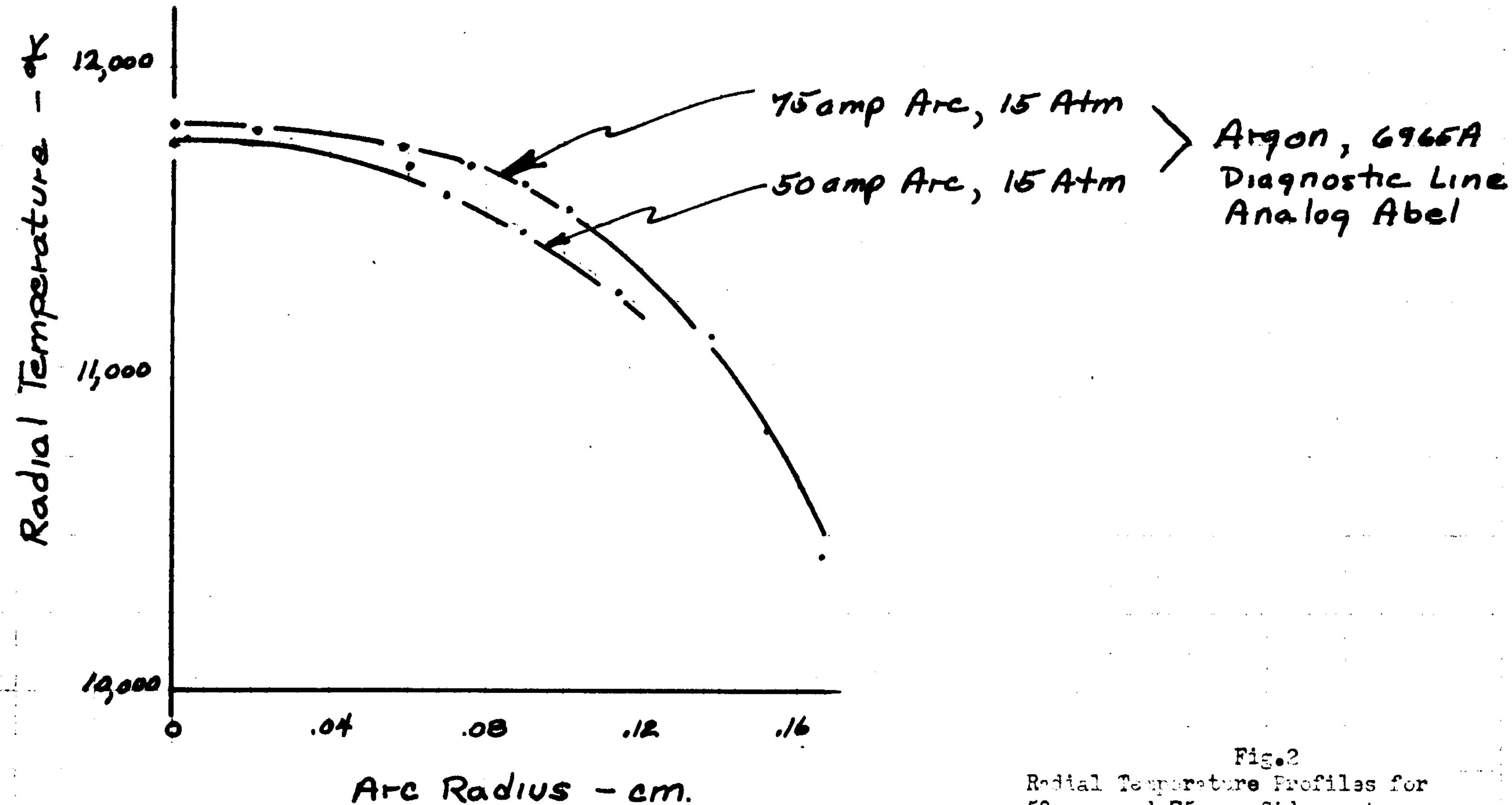


Fig.2
Radial Temperature Profiles for
50 amp and 75 amp Side-on Arcs

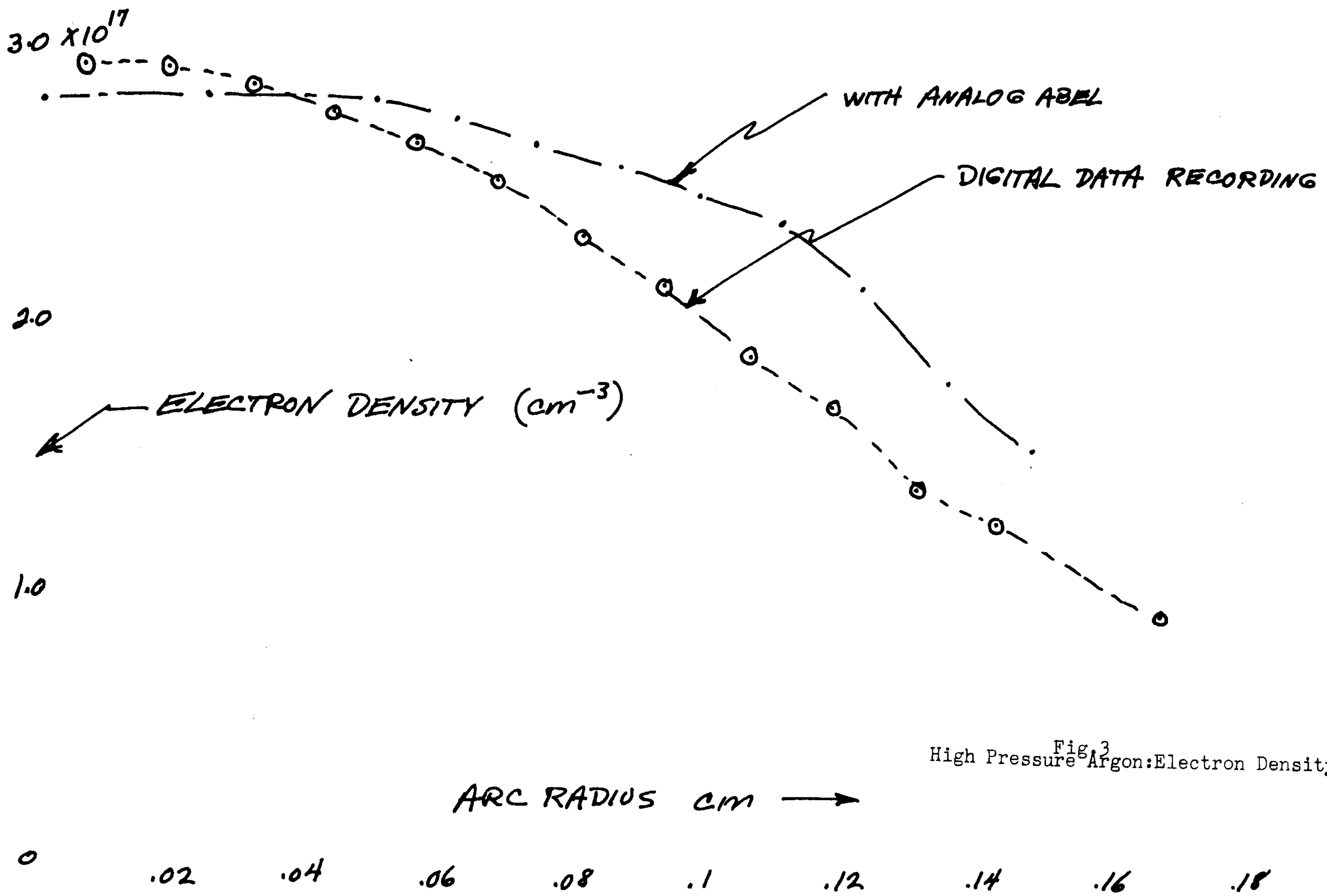


Fig. 3
High Pressure Argon:Electron Density

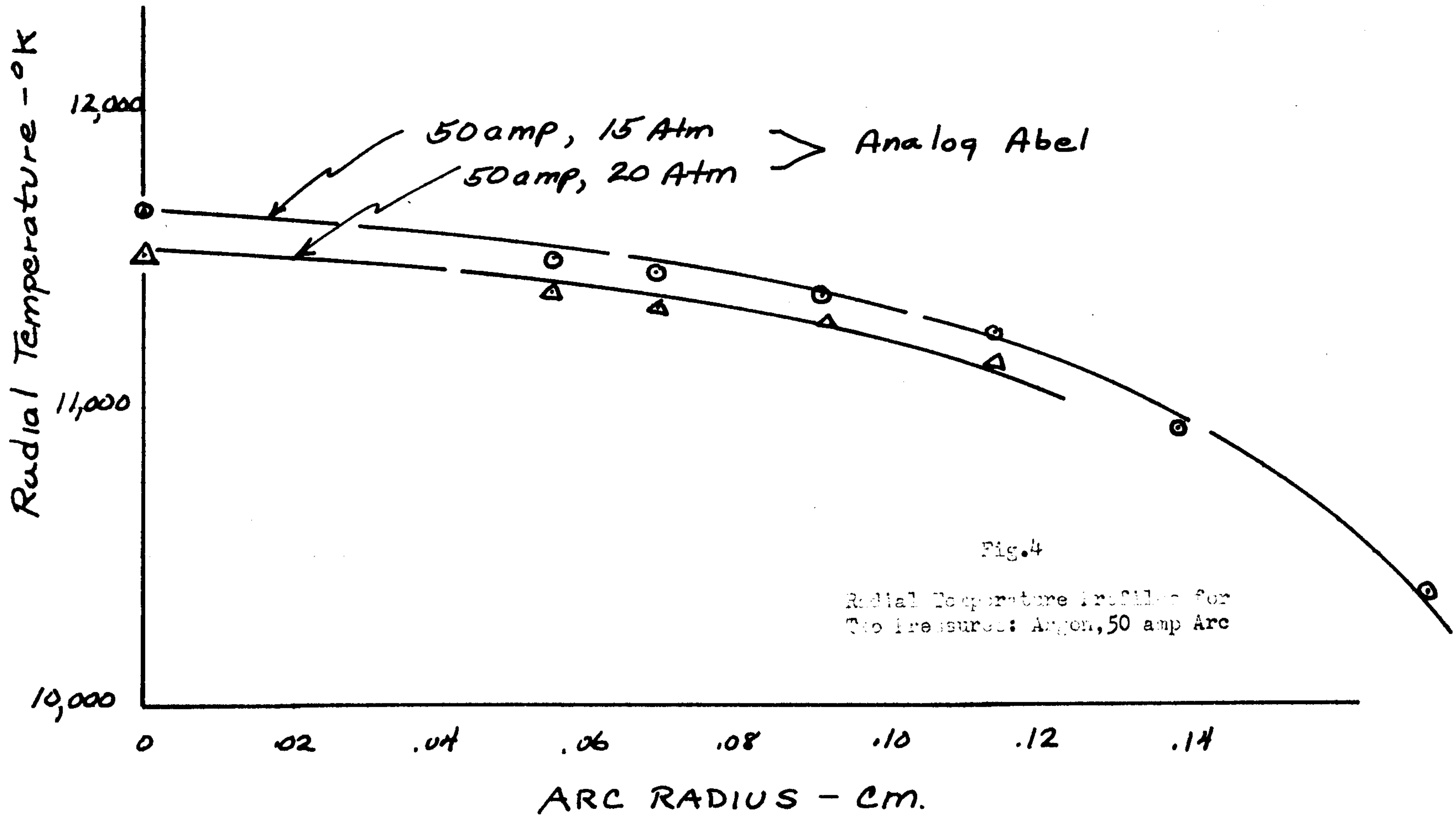


Fig.4

Radial Temperature Profiles for Two Pressures: Argon, 50 amp Arc

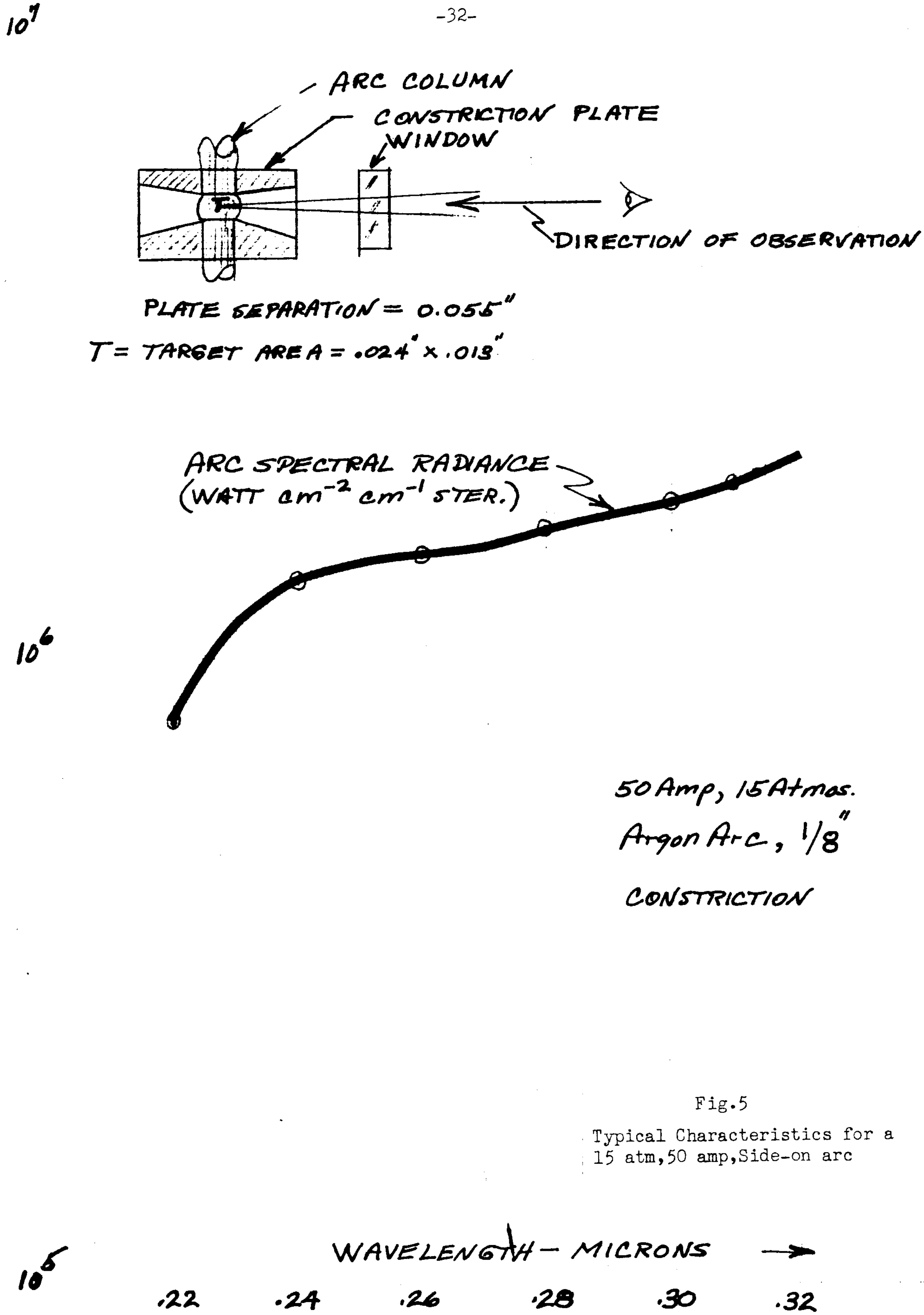


Fig.5

Typical Characteristics for a 15 atm,50 amp,Side-on arc

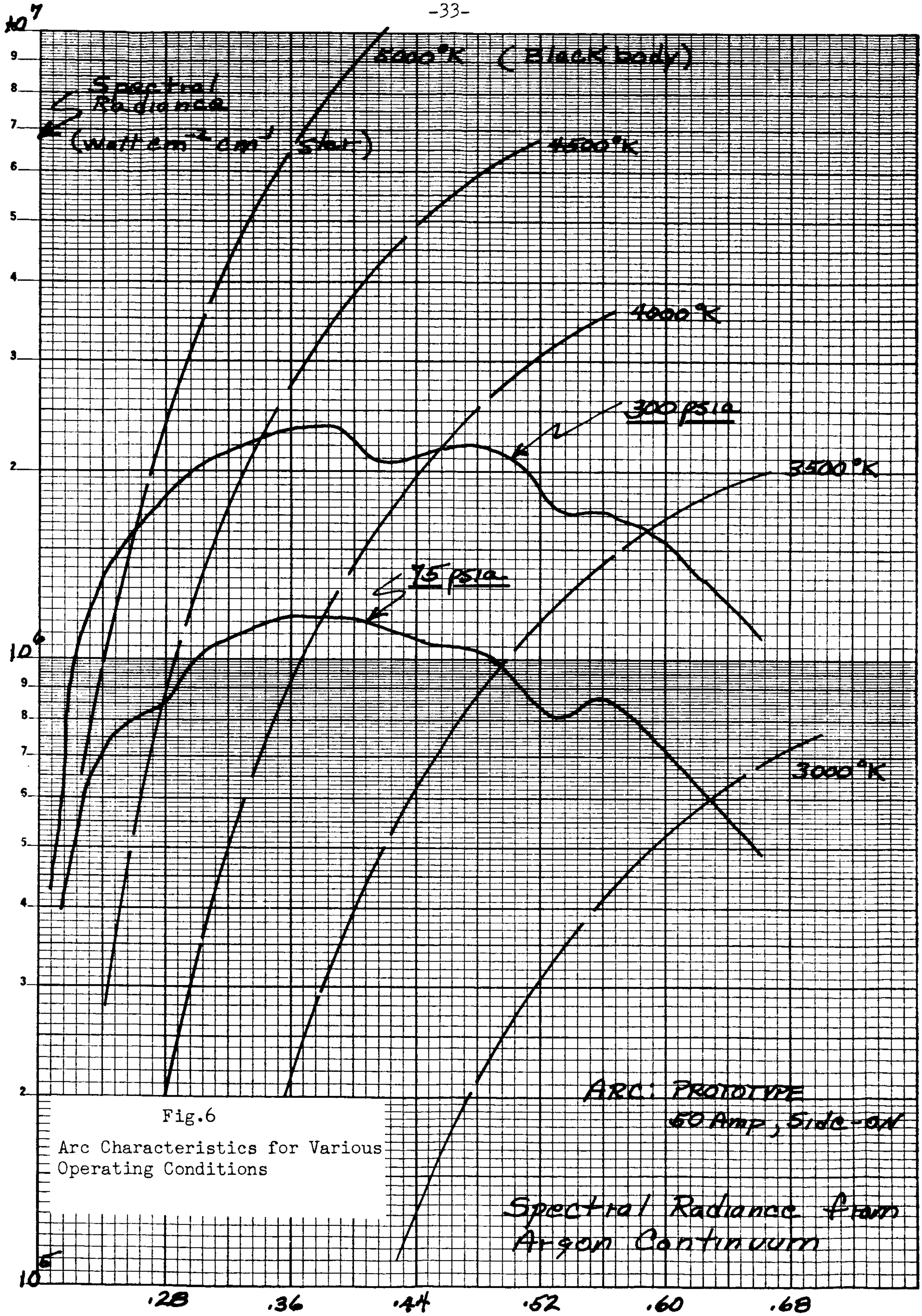


Fig.6

Arc Characteristics for Various Operating Conditions

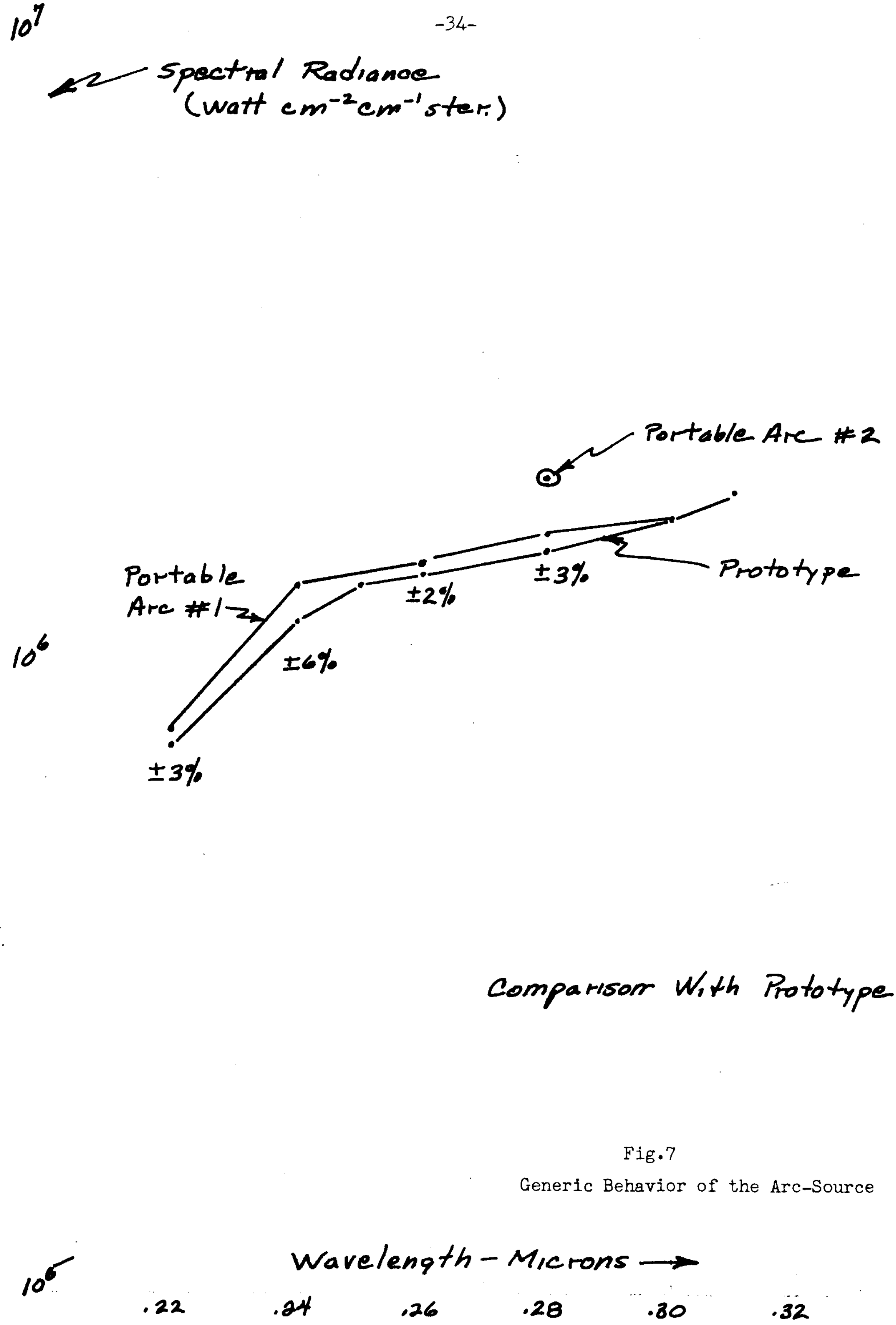


Fig.7

Generic Behavior of the Arc-Source

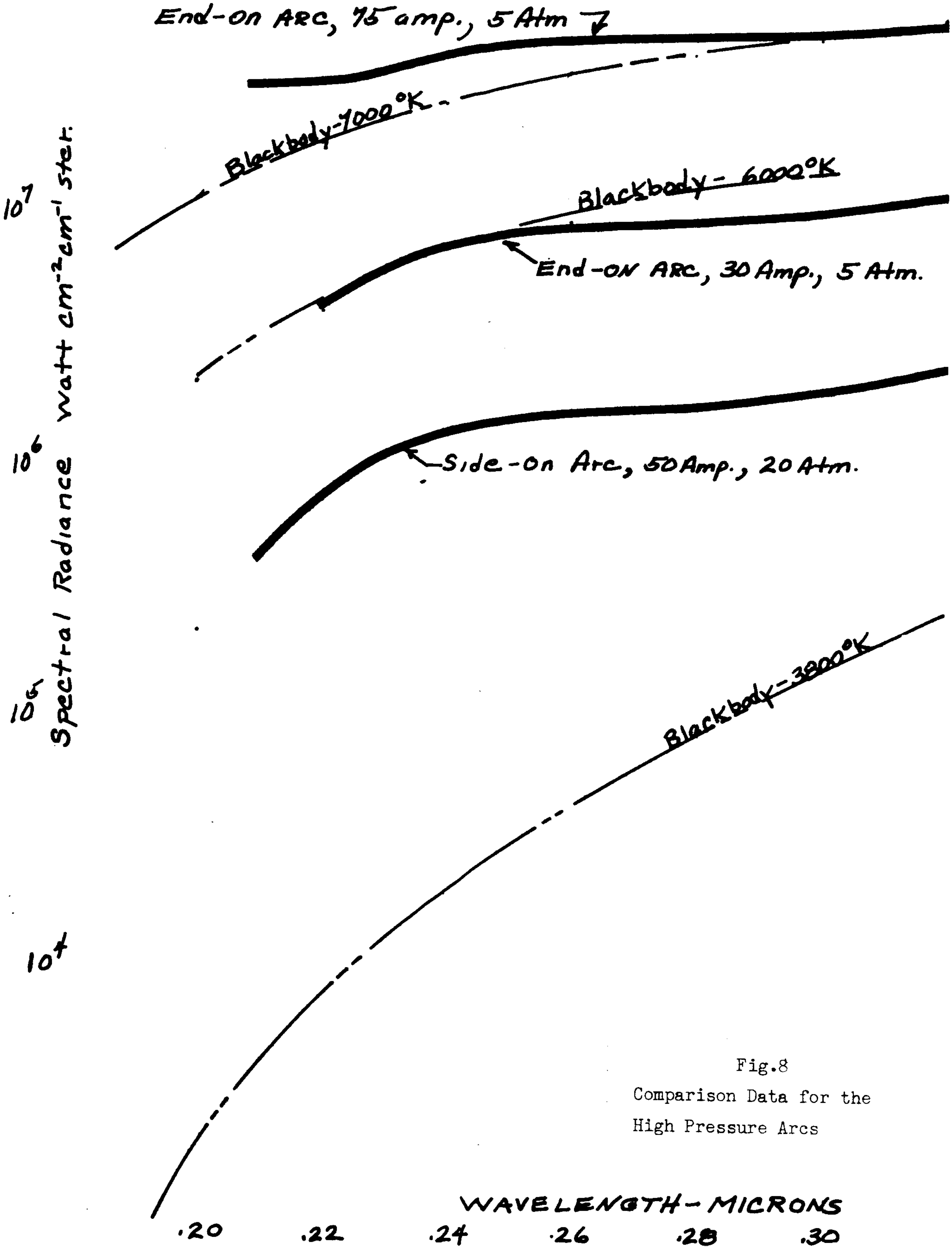


Fig.8
Comparison Data for the
High Pressure Arcs

APPENDIX

Figures

Tables

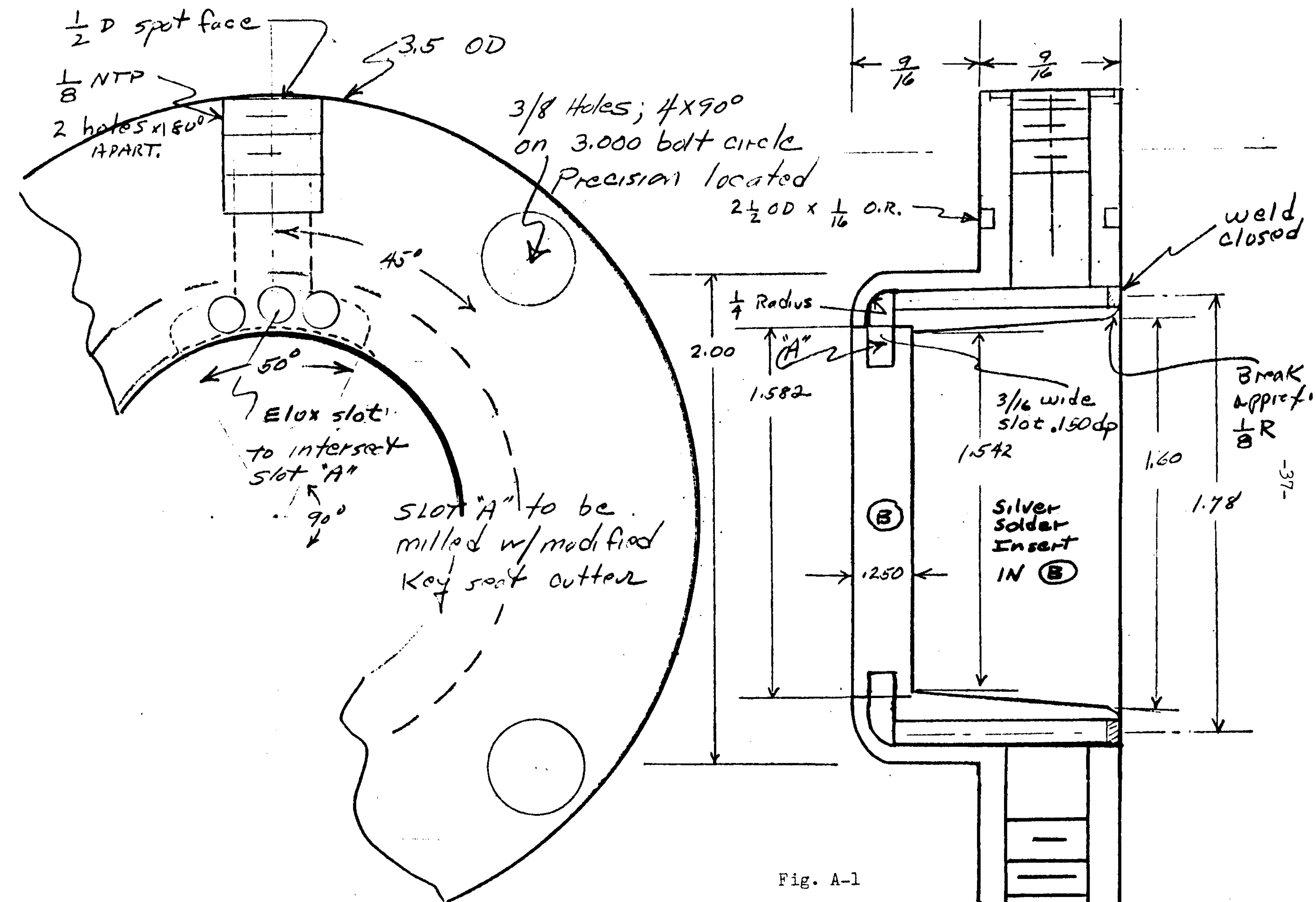


Fig. A-1
High Pressure Arc
2nd and 3rd Constriction Flange

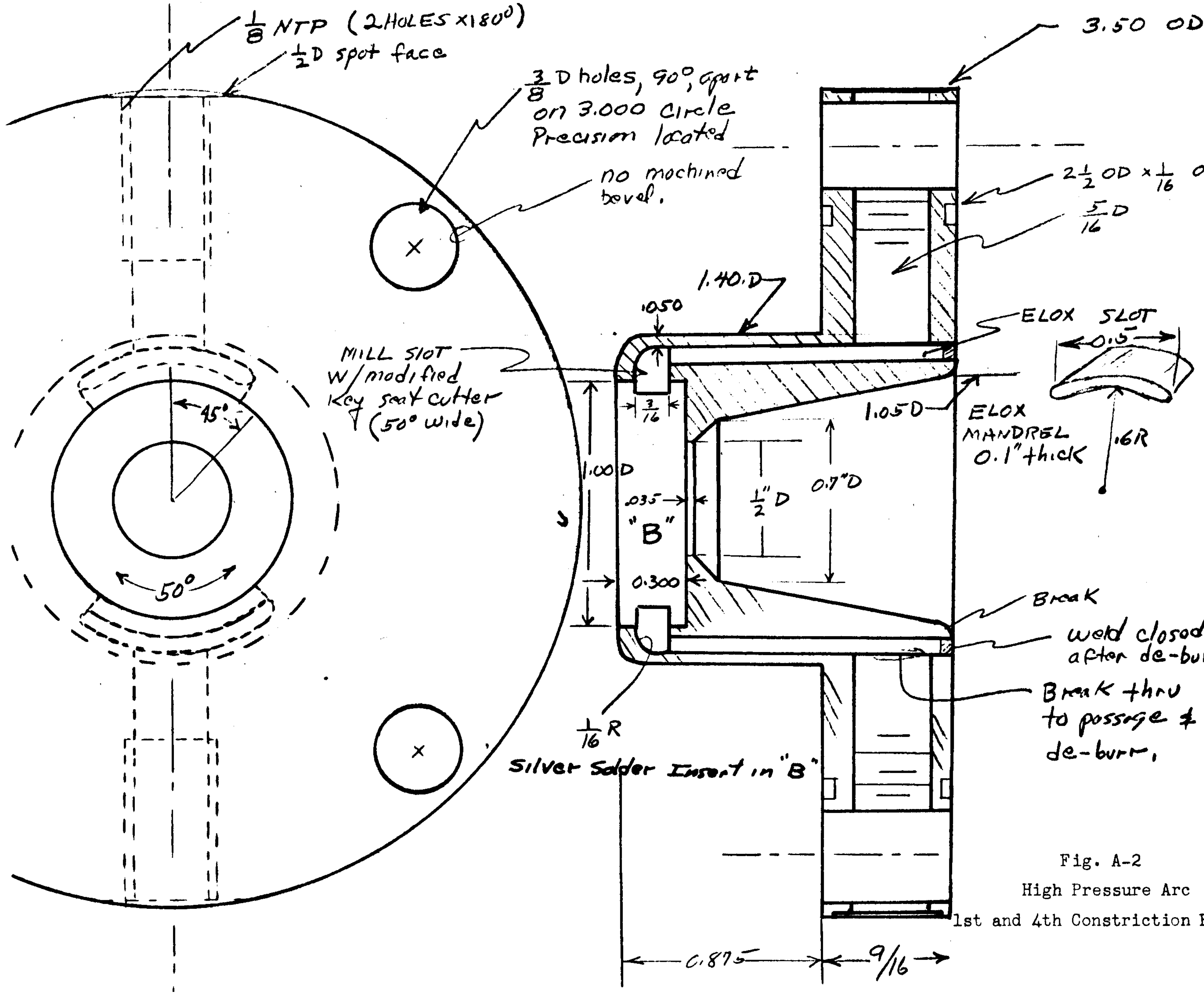


Fig. A-2
High Pressure Arc
1st and 4th Constriction Flange

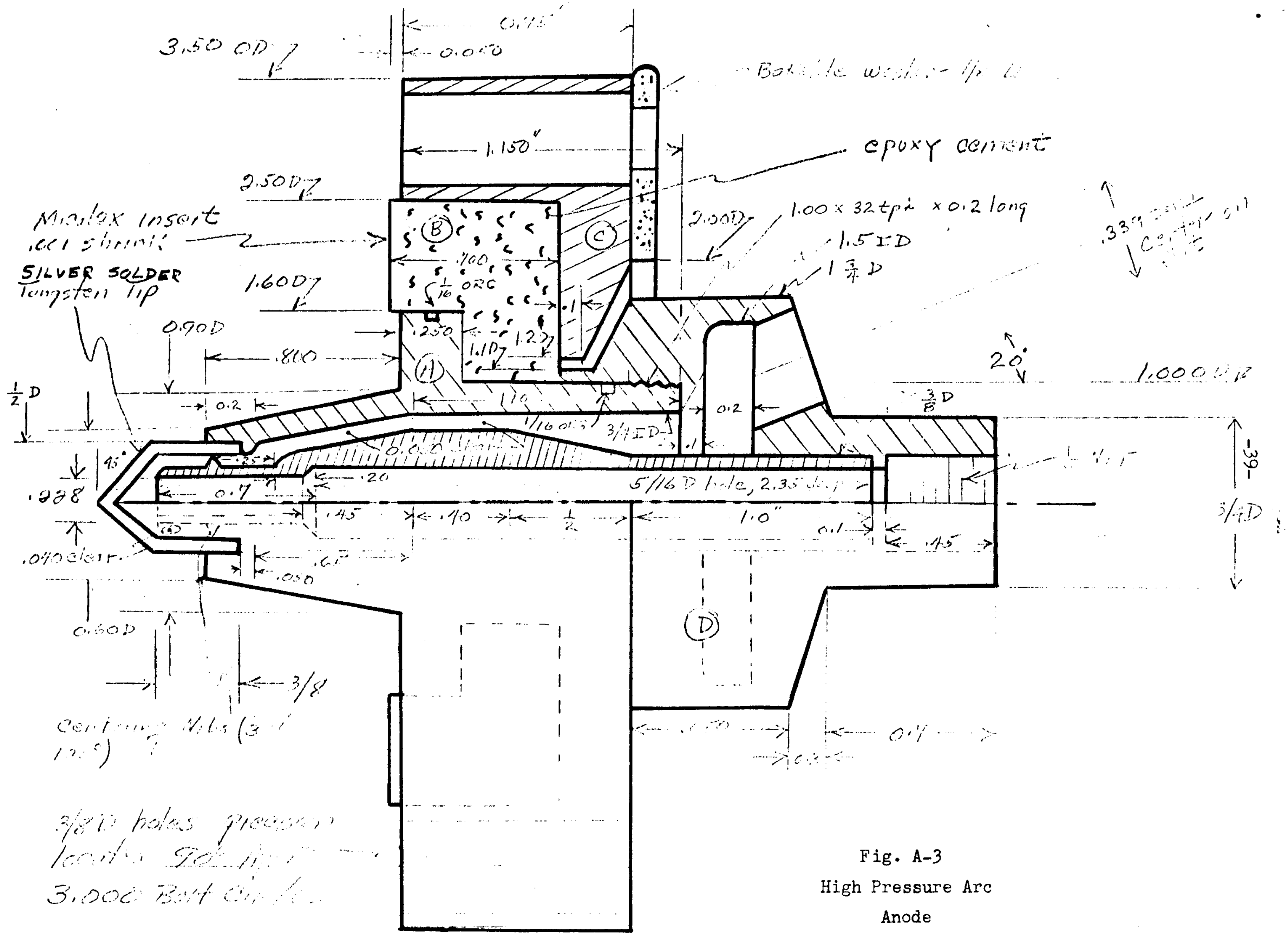


Fig. A-3
High Pressure Arc
Anode

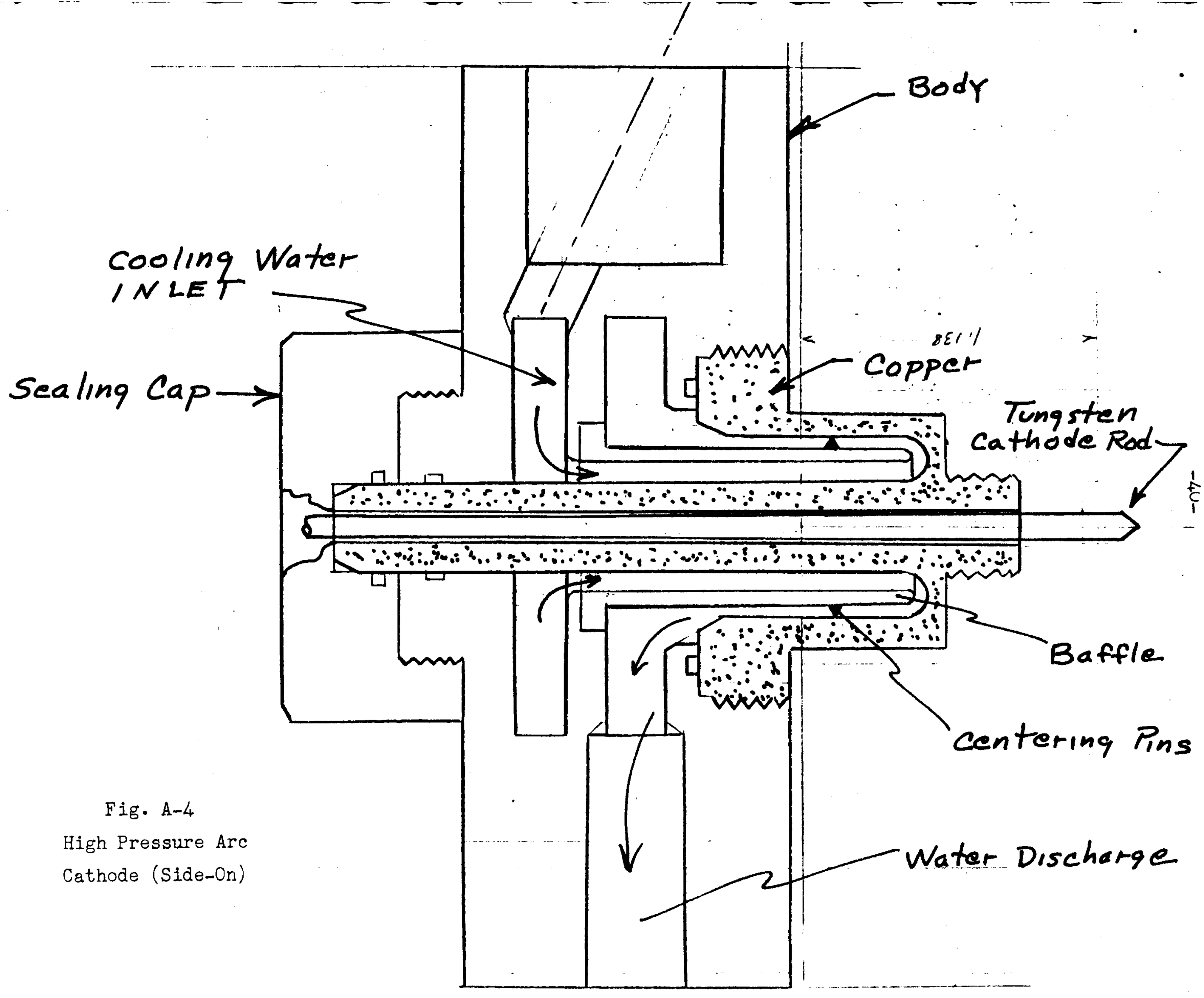


Fig. A-4
High Pressure Arc
Cathode (Side-On)

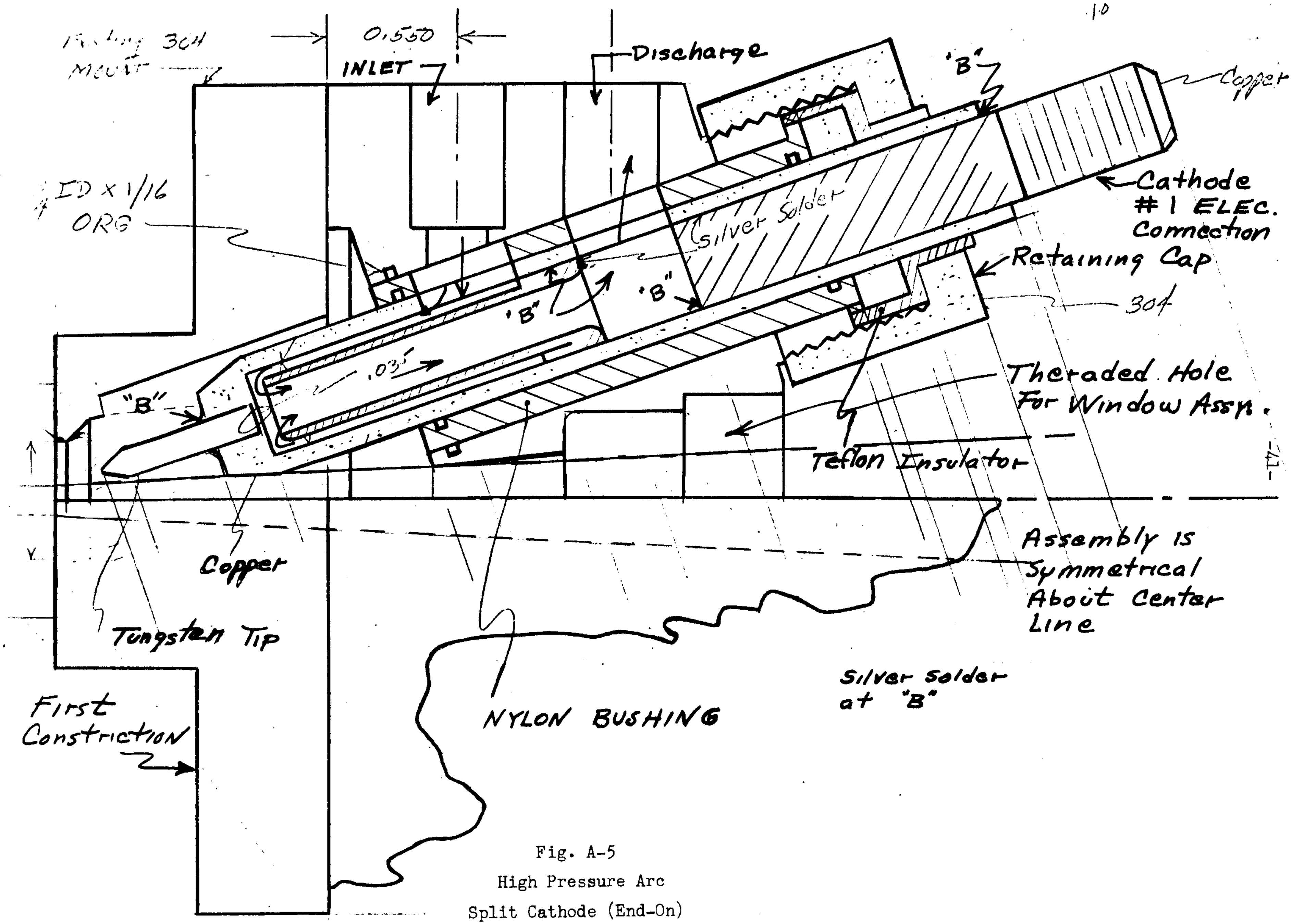


Fig. A-5
High Pressure Arc
Split Cathode (End-On)

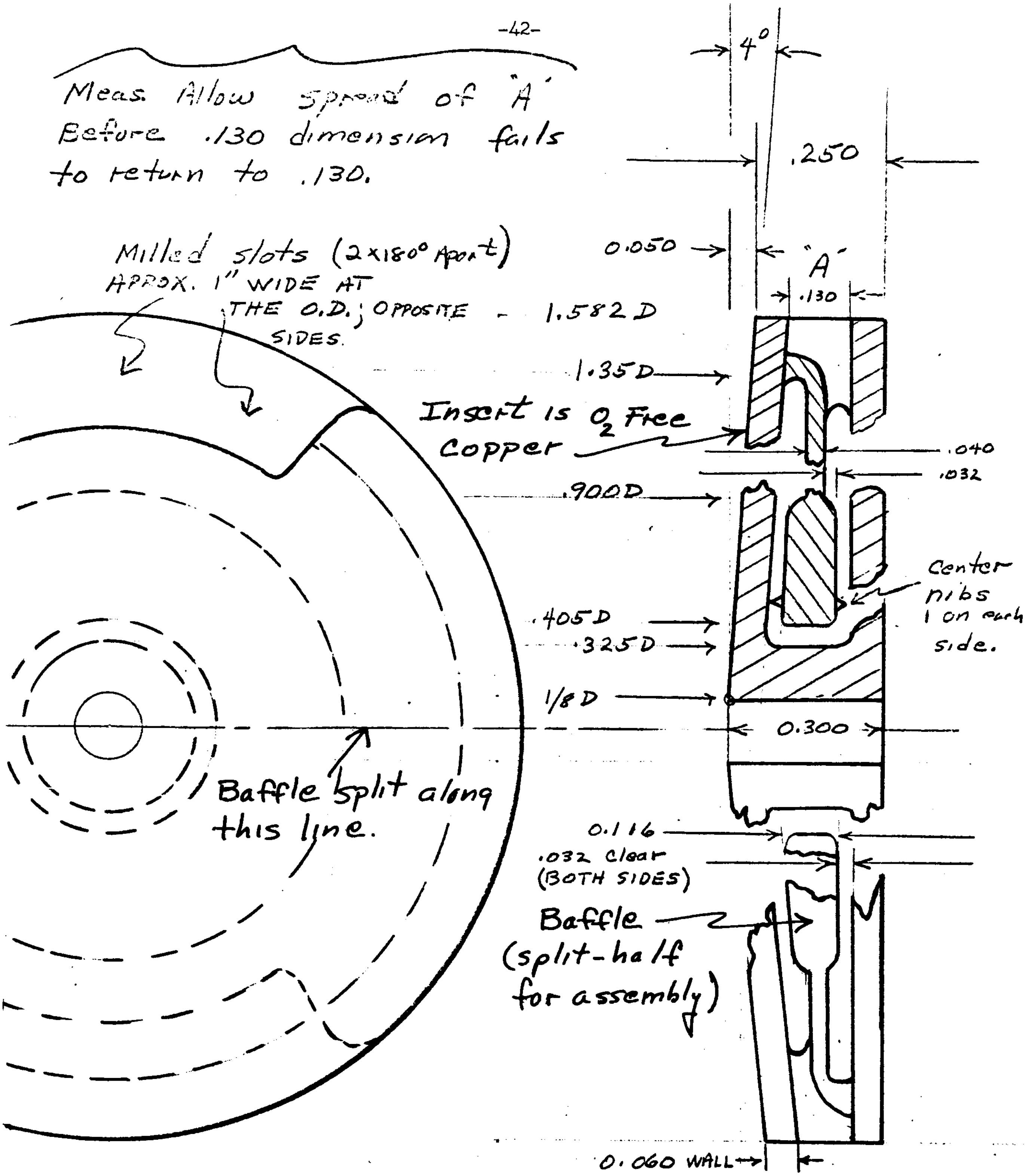


Fig. A-6
Inserts for the Constriction Flanges

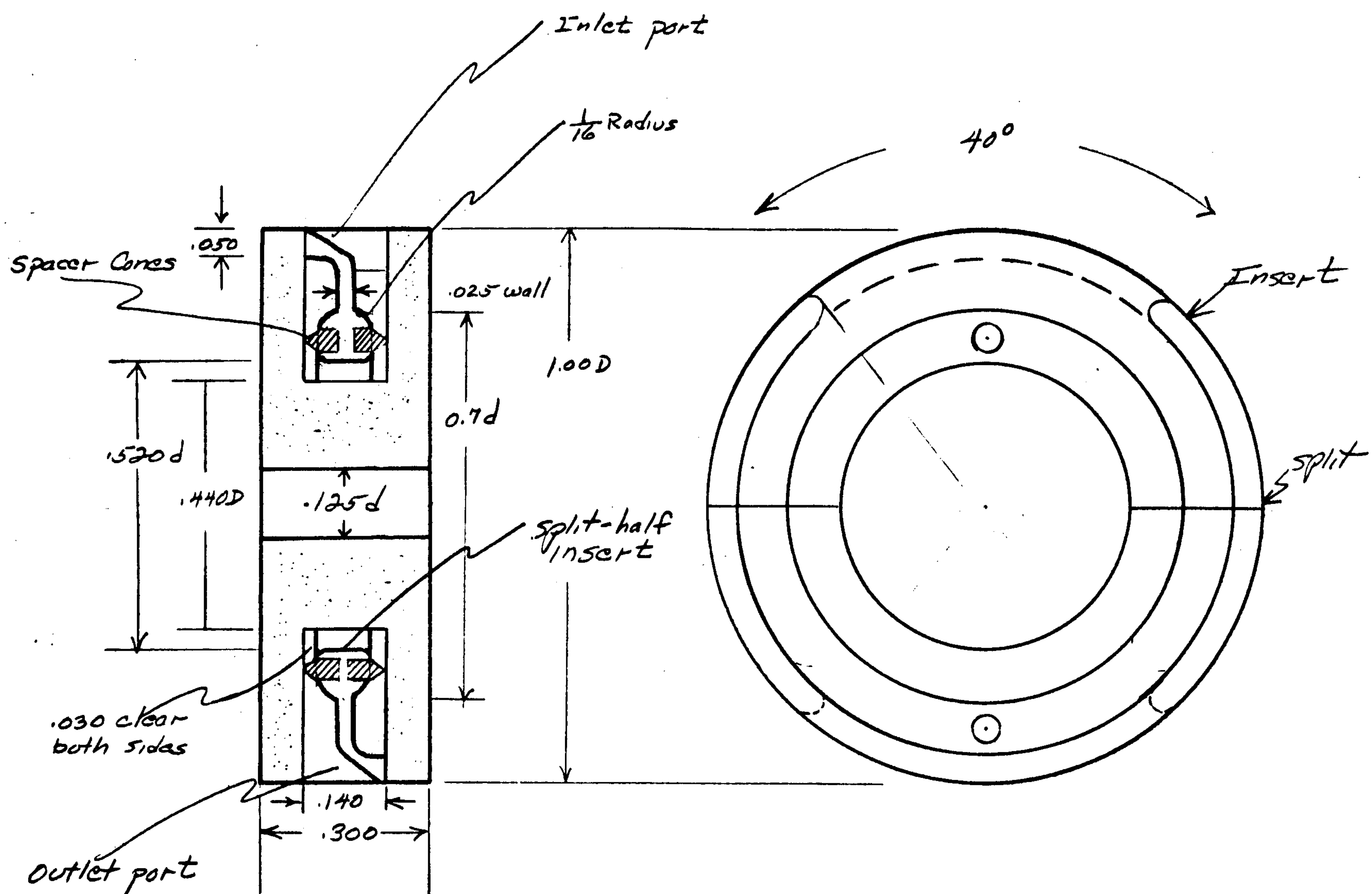


Fig.A-7
Inserts for the Constriction Flanges

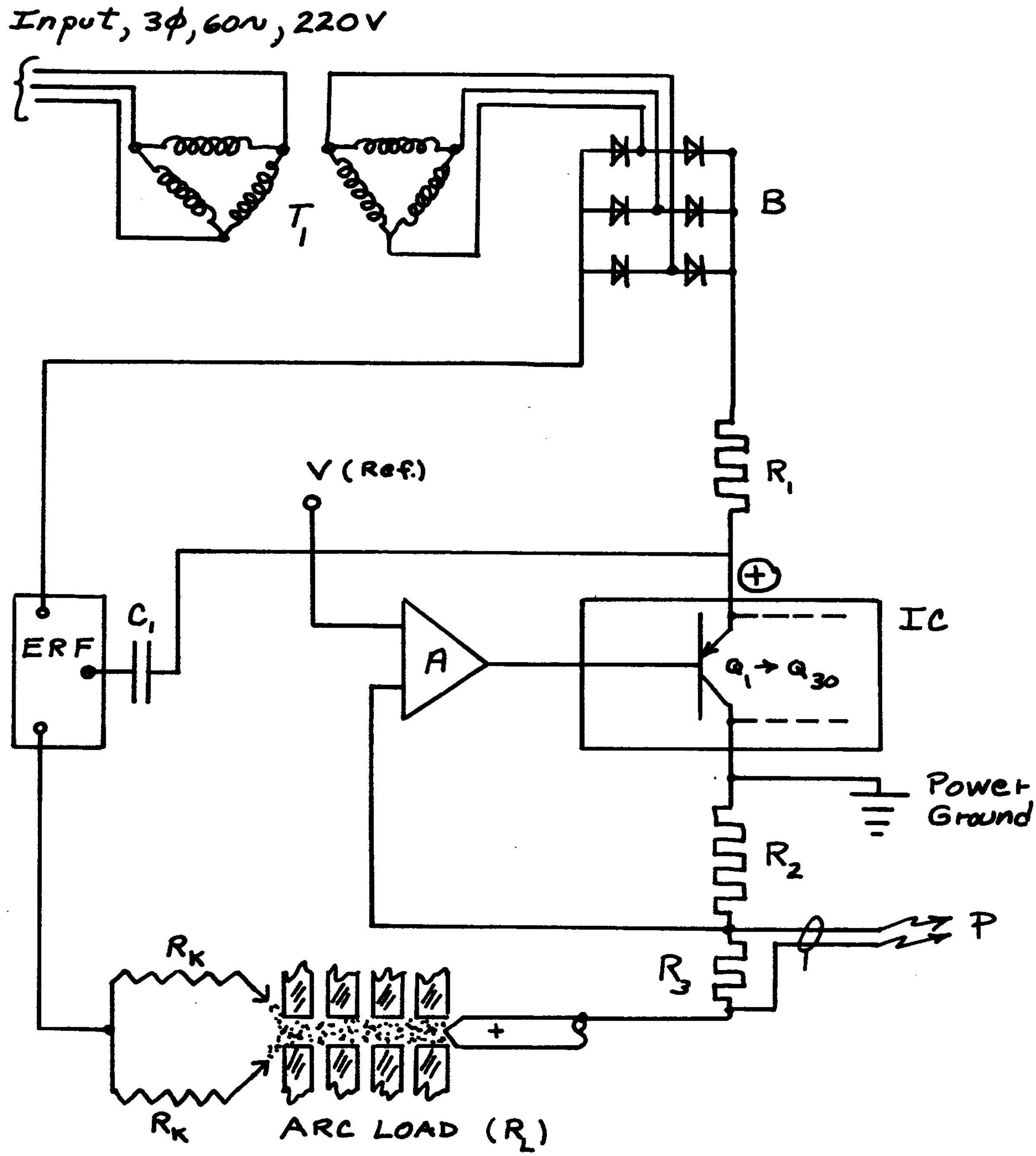


Fig.A-8 Power Supply Schematic

P, Potentiometer
R_1, Ballast, 0-5Ω
R_2, Control Shunt 0.2Ω
R_3, Current Shunt

R_K, Balance, 7Ω
IC, Current Control
A, Control Amp.
B, 3φ, Full Wave Bridge 300 A max.

C_1, Capacitor, 120nf
T_1, Isolation Trans, 30 KVA
ERF, Electronic Ripple Filter
R_L, Equivalent Arc Resistance, 2.2Ω at 30 Amp.

OPTICAL SCHEMATIC

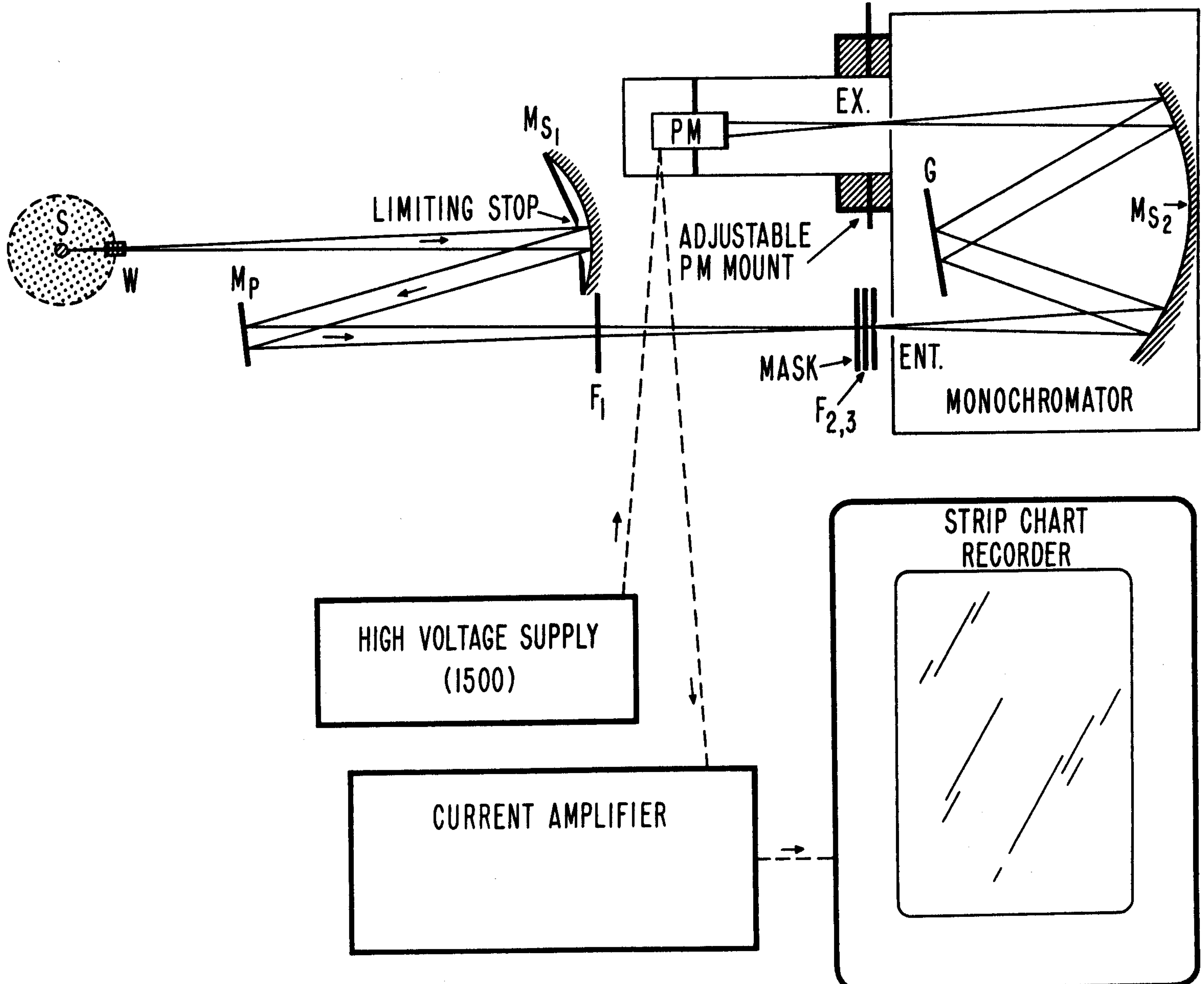


Fig.A-9

Optical Schematic for the Measurements

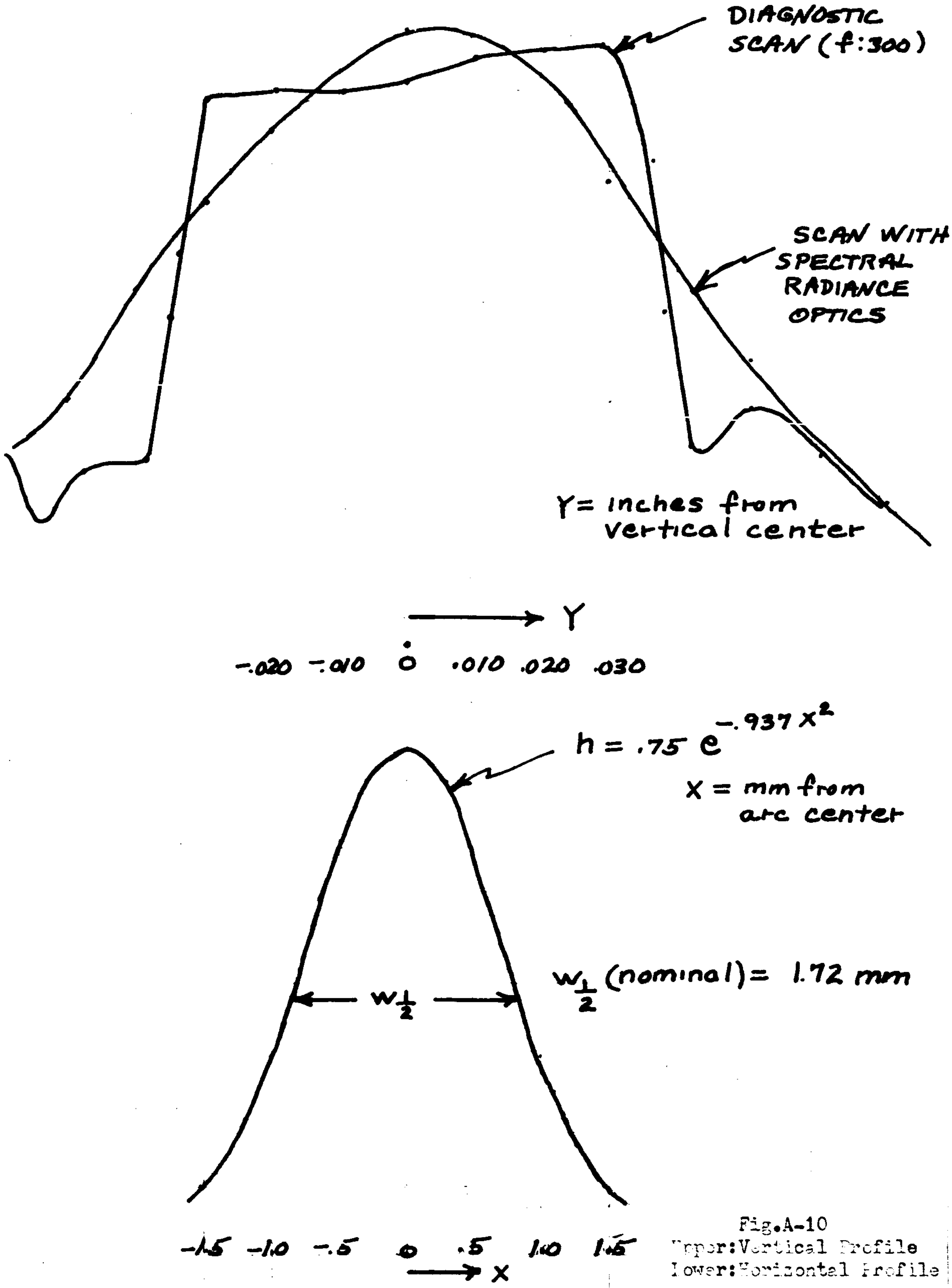


Fig.A-10
Upper:Vertical Profile
Lower:Horizontal Profile

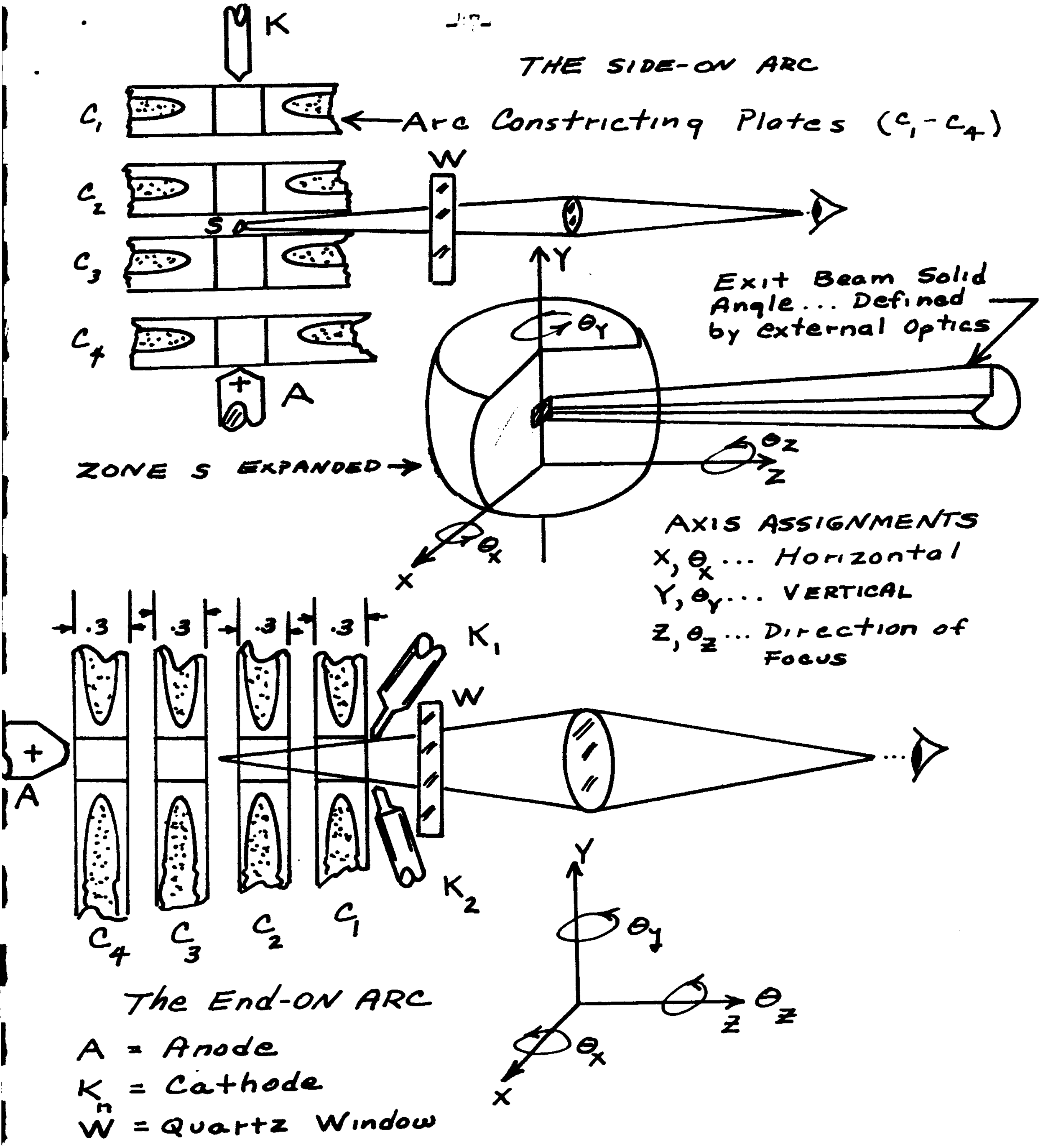


Fig.A-11
Schematic Diagram for the Modes of Operation

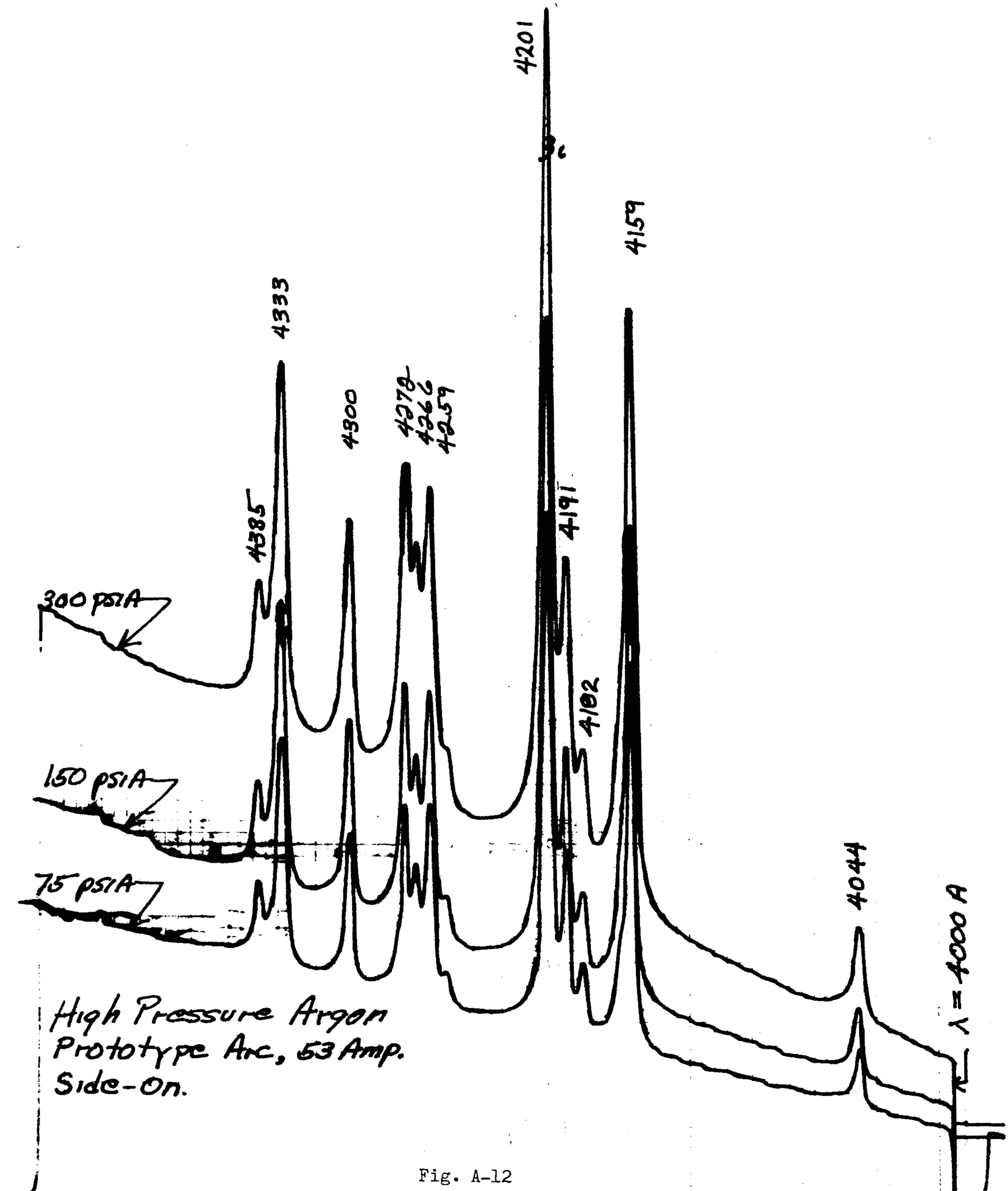


Fig. A-12

Typical Line Spectrum for Three Pressures

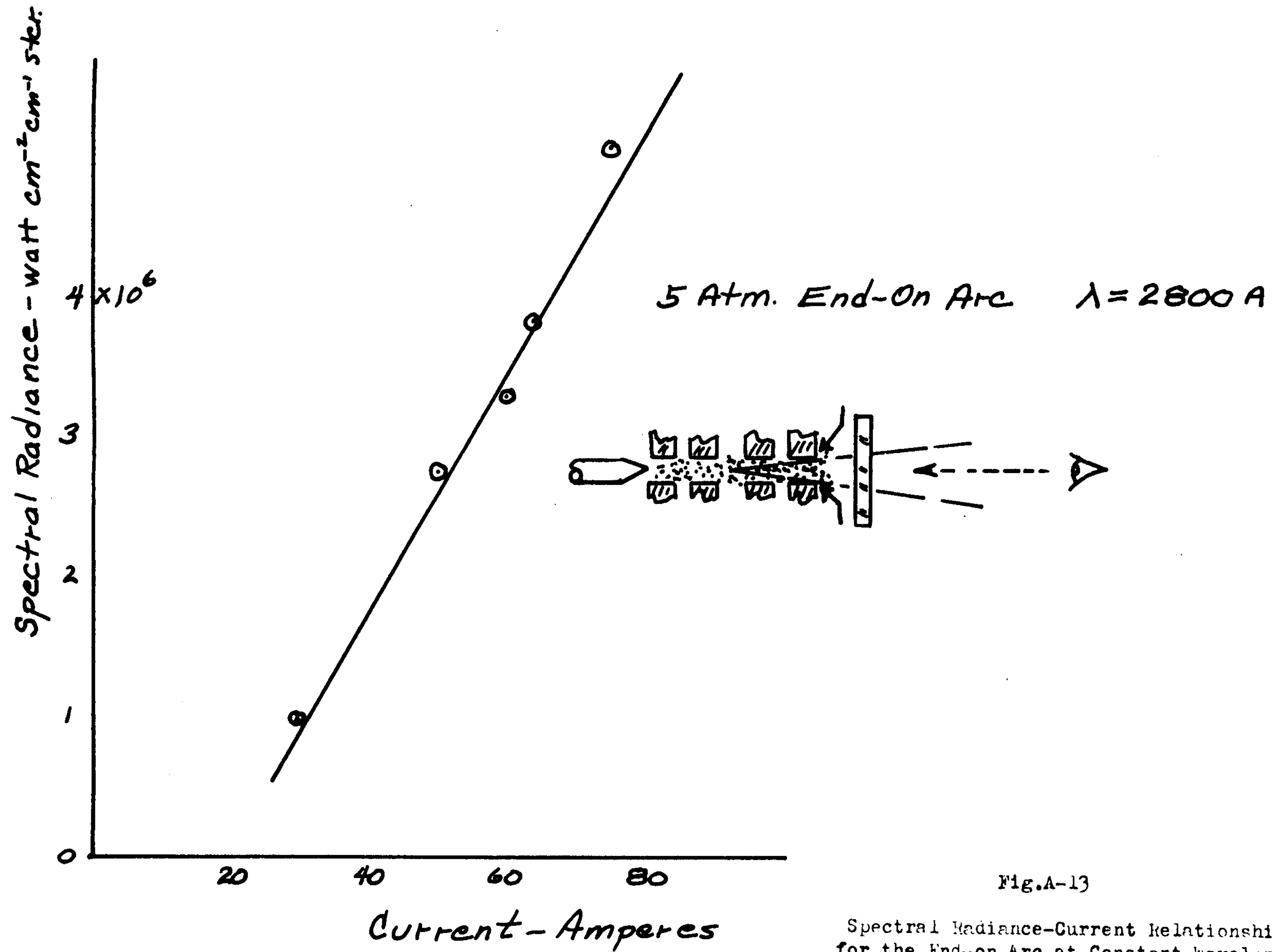


Fig.A-13

Spectral Radiance-Current Relationship
for the End-on Arc at Constant Wavelength

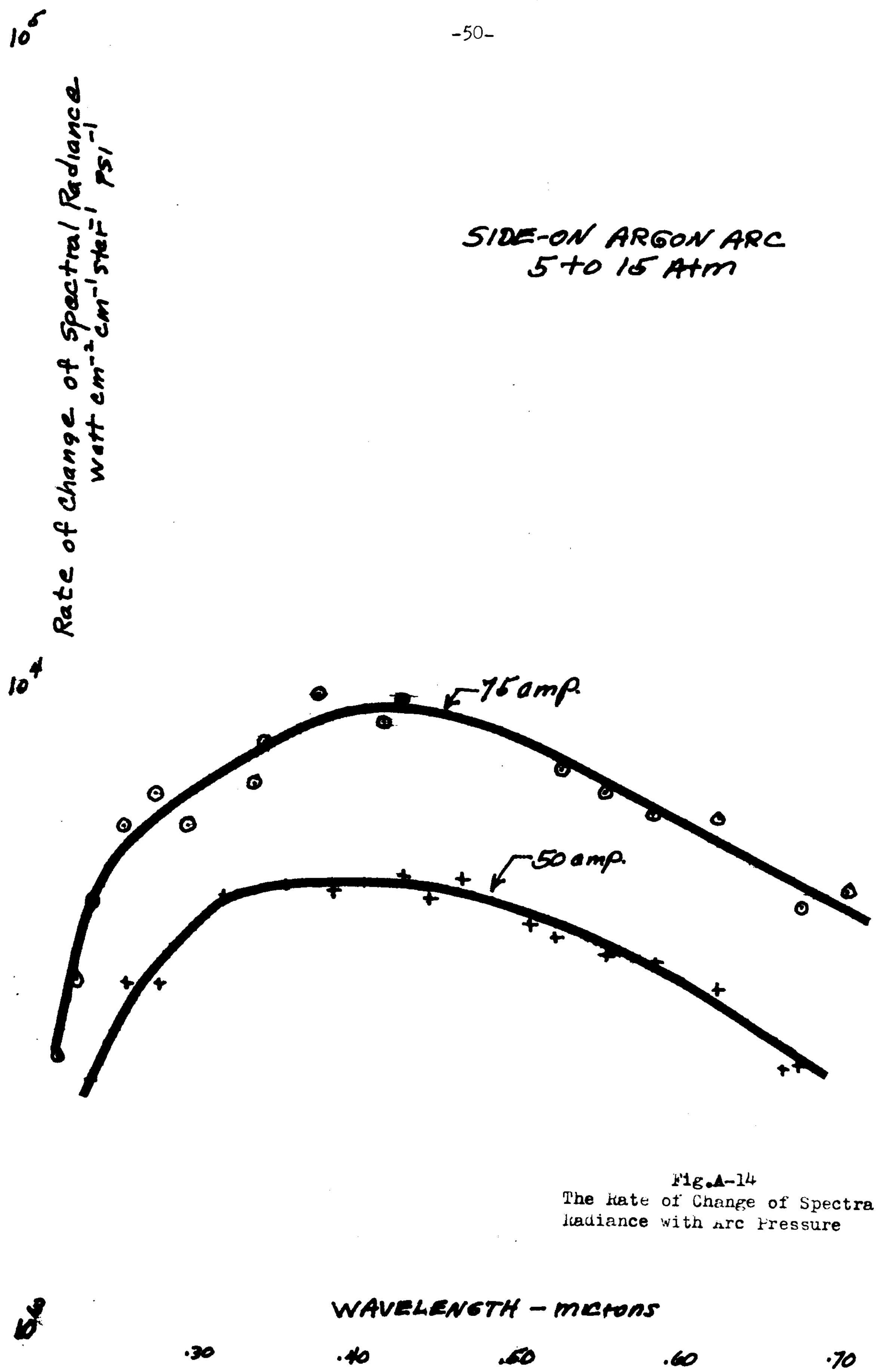


Fig.A-14
The Rate of Change of Spectral Radiance with Arc Pressure

TABLE A-1

Element	Characteristic
1. Power supply	30 to 75 amp, 300 V, constant current (±30 ma), 0.2% ripple
2. Cooling	water, 50 psig, 7 gal/min max
3. Argon flow	Flow meters - cathode 70-9000 ml/min, anode 3-270 ml/min, intermediate (2) 7-1400 ml/min, needle valve adjustment, manual flow control.
4. Argon pressure	Controlled ±1/4 psi to 300 psi, measured with precision pressure gage ±.1% accuracy.
5. Arc mount	Mechanically stable for weight of 30 pounds, provision for x, y, and z translations. Rotations about the x and y axes are required.

TABLE A-2

Zone	Flow (nominal, ml/min)	Control	Sensitivity
Cathode	7500	manual or regulated	3
1st and 2nd Constriction	100	manual (needle valve)	25
3rd and 4th Constriction	100	" " "	25
Anode	400	" " "	10

The flow ratios are the exhaust gas flows measured on the low pressure side of the flow adjusting needle valves. The data is for the side-on arc.

*Sensivity is the percent flow change required for a 1% change in the measured spectral radiance.

PART II

HIGH ACCURACY SPECTRAL RADIANCE CALIBRATIONS

H. J. Kostkowski
D. E. Erminy
A. T. Hattenburg

INTRODUCTION

During the past year, H. J. Kostkowski, D. E. Erminy, and A. T. Hattenburg of NBS reported the capability of determining spectral radiance of tungsten strip lamps with an uncertainty of less than 1%. In the lecture this morning I would like to tell you about this work, particularly those aspects that might be generally useful in radiometry.

The approach that was used in the spectral radiance determination was the classical method of comparing the source to a blackbody. This method was undertaken because it is the basis of radiation pyrometry where, at least at one wavelength and relative to the International Practical Temperature Scale, considerable success had been achieved, and we were quite familiar with the techniques recently developed in this area.

It is generally accepted that the spectral radiance of a blackbody is given by the Planck radiation equation

$$N_{b\lambda} = C_1 \lambda^{-5} / (e^{C_2/\lambda T} - 1) \tag{1}$$

Experimental verification of this equation has probably not been accomplished to better than about 5%. Nevertheless, because of its strong theoretical basis, we will also assume that the above relation is exact. Therefore a spectral comparison of a source with a blackbody will result in the determination of the spectral radiance of the source with an accuracy which depends on the accuracy of C_1, C_2, λ, T, the quality of the blackbody, and the accuracy of the comparison. Our initial goal was a total uncertainty of 1% or less, in the visible. Therefore, we tried to keep individual sources of error in terms of spectral radiance to about 0.1%. Let us check how well the above constants are known and how well the other parameters would have to be determined to achieve our goal.

REQUIREMENTS

Accuracy of C_1. The first radiation constant C_1 is related to the atomic constants c and h in the following manner

$$C_1 = 2C^2h$$

The Committee on Fundamental Constants of the National Academy of Science, National Research Council recommends the following value

$$C_1 = 1.19096\ 10^{-12} \text{ watts cm}^2 \text{ sterad}^{-1}$$

The Committee estimates an uncertainty in C_1 in terms of two standard deviations or a 95% confidence factor of .0054%. Thus C_1 is reported to be known about 20 times better than our .1% objective.

Accuracy of C_2. The second radiation constant C_2 is related to the atomic constants by the relation

$$C_2 = \frac{hc}{k}$$

and the above Committee recommends a value of C_2 = 1.43879 cm degrees with an uncertainty in terms of two standard deviations of .0083%. This corresponds to an error of .089% for the spectral radiance in Eq. (1) at a wavelength of 5500 A and a temperature of 2500°K. Thus C_2 is also known sufficiently well for our 0.1% criterion.

Wavelength accuracy. The wavelength accuracy required in comparing a blackbody to a strip lamp can easily be obtained from Eq. (2) which is used in optical pyrometry when relating the brightness temperature T_1 at one wavelength λ_1 to the brightness temperature T_2 at another wavelength λ_2 and to the color temperature T_c,

$$\frac{T_1 - T_2}{T_1 T_2} = \frac{\lambda_2 - \lambda_1}{\lambda_1}\left(\frac{1}{T_1} - \frac{1}{T_c}\right) \cong \frac{\Delta T}{T_1^2} \qquad (2)$$

Using Wien's Equation for an approximation to Planck's Equation i.e. dropping the -1 in Eq. (1) and differentiating Wien's Equation with respect to T one obtains

$$\frac{\Delta N}{N} = \frac{C_2}{\lambda T} \frac{\Delta T}{T} \tag{3}$$

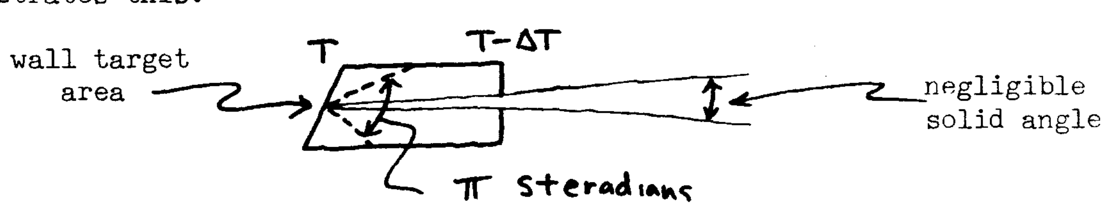
Combining this with Eq. (2), we have

$$\frac{\Delta N}{N} \cong \frac{C_2 \Delta\lambda}{\lambda^2}\left(\frac{1}{T_1} - \frac{1}{T_c}\right) \tag{4}$$

Assuming $\frac{\Delta N}{N}$ = .001, T_1 = 2500 °K, λ = 6500A and obtaining $T_c \cong$ 2860°K from the Handbook of Physics and Chemistry, one obtains $\Delta\lambda \cong$ 6 Angstroms. This then is the maximum uncertainty permitted in the wavelength calibration of the monochromator to be used in comparing the blackbody to the strip lamp.

Accuracy of Blackbody Temperature. The uncertainty permitted for the temperature of the blackbody can be obtained from Eq. (3). Solving for ΔT for λ = 5500 A, $\frac{\Delta N}{N}$ = .001 and T = 2500°K results in ΔT = .24 deg.

Blackbody Quality. The blackbody must for our criterion of 0.1% be stable and have an emissivity of at least 0.999. A rough estimate of the permissible temperature non-uniformity can be obtained as follows. Assume that the emissivity of the cavity material is 0.9 (reasonable value for graphite which will be used) and the walls of the cavity have either a temperature T or T - ΔT, each irradiating the wall target area equally. The figure below illustrates this.



Then

$$N_\lambda\binom{\text{wall}}{\text{target}} \cong .9\,N_{b\lambda}(T) + .1 \times .5\,N_{b\lambda}(T) + .1 \times .5\,N_{b\lambda}(T-\Delta T)$$

$$\cong .95\,N_{b\lambda}(T) + .05\left[N_{b\lambda}(T) - \frac{\Delta N}{\Delta T}\Delta T\right]$$

and using Eq. (3)

$$= .95\,N_{b\lambda}(T) + .05\left[N_{b\lambda}(T) - \frac{C_2}{\lambda T^2}\,N_{b\lambda}(T)\,\Delta T\right]$$

$$N_\lambda\binom{\text{wall}}{\text{target}} = N_{b\lambda}(T)\left[1 - .05\,\frac{C_2}{\lambda T^2}\,\Delta T\right]$$

$$\frac{N_\lambda\binom{\text{wall}}{\text{target}}}{N_{b\lambda}(T)} = \epsilon_{\text{effect.}} = 1 - .05\,\frac{C_2}{\lambda T^2}\,\Delta T$$

Using effective = 0.999, T = 2500°K and λ = 5500 A, $\Delta T \cong 5°$.

Accuracy of Comparison. The accuracy of the comparison of $N_{b\lambda}$ to N_λ must be .999% and N_λ should not drift by more than 0.1% in 10 hours.

These then are the general requirements. I'd like now to discuss the design and techniques utilized in realizing the above requirements and the results obtained.

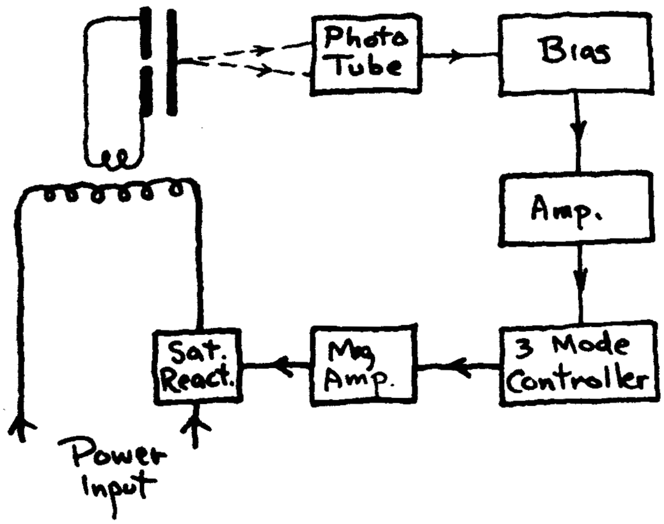
THE BLACKBODY

The blackbody used is shown in Fig. 1. It was fabricated of graphite because

1. It could be used to about 3000°K and could be used without an extremely pure inert atmosphere. The latter statement also made it possible to use without a window by simply flushing the housing with an inert gas. Not having to make a correction for the window would improve the accuracy.

2. Its emissivity was already high and it could be easily machined and handled.

The following block diagram shows the control system used. With this system it has been possible to limit the instability and drift to about 0.1% over a 30 to 45 minute period. This is sufficient time in which to determine the blackbody temperature, make a comparison at some wavelength and again check the temperature.



Limiting the temperature non-uniformity to about 5 deg was achieved by modifying the shape of the graphite tube until when sighting with an optical pyrometer (a visual instrument was just adequate) at the cavity hole on the side or at the various holes from above, no temperature differences larger than 5 deg were observed. When looking from the top at the various holes along the axis of the tube, it was possible to get those, one section removed from the main cavity, to have the same brightness i.e. to disappear. This corresponds to about 5 deg. at 2500 °K.

The emissivity of the blackbody cavity depends on the geometry and dimensions of the cavity and on the partial reflectivity of the material, particularly the wall opposite the cavity sighting hole. To a first approximation, which is usually quite good in high quality cavities,

$$\epsilon = 1 - r\Omega \tag{5}$$

where r is the partial reflectivity and Ω is the solid angle originating at the wall target and subtended by the cavity opening, Fig. a. The partial

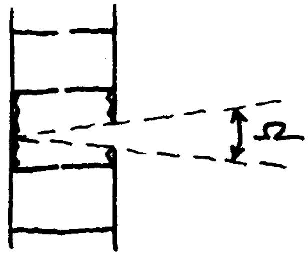


Fig. a.

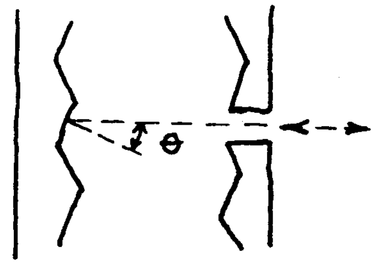


Fig. b.

reflectivity of the wall target, relative to an incident and reflected angle θ with respect to the cavity hole, was made small by having the wall shaped like a course thread, Fig. b. Laboratory measurements at room temperature which could easily be performed with a visual pyrometer, indicated a partial reflectivity of $r \cong .02$ sterad^{-1}. Using Eq. (5) with an $\varepsilon = .999$ and $r = .02$ sterad^{-1}, the required Ω is .033 sterad. Thus, since the depth of the cavity is about 10 mm , using

$$\Omega = \pi d^2/4(10)^2$$
$$d \cong 2 \text{ mm}$$

This is the cavity hole diameter usually used.

It would be desirable to confirm the emissivity of .999 through a more direct measurement. We thought of a way to do this. It consists of making changes in Ω and r and determining the relative change of spectral radiance at two widely spaced wavelengths say 3250 A and 6500 A. A convenient equation to use in predicting the change is

$$\frac{N_{\lambda'}^{(2)}}{N_{\lambda'}^{(1)}} = \frac{\left(\frac{\epsilon_1(\lambda)\,\tau_1(\lambda)}{\epsilon_2(\lambda)\,\tau_2(\lambda)}\right)^{\lambda/\lambda'}}{\frac{\epsilon_1(\lambda')\,\tau_1(\lambda')}{\epsilon_2(\lambda')\,\tau_2(\lambda')}} \tag{6}$$

Eq. (6) was derived assuming Wien's Equation is valid and expresses the ratio of spectral radiance of source 2 to that of source 1 at a wavelength λ' when the two sources are adjusted to have the same spectral radiance at wavelength λ. The ε's and τ's are the spectral emissivities of the source and spectral transmittances of any window respectively. Since no windows are present and if we assume that the sources are gray bodies Eq. 6 becomes

$$\frac{N_{\lambda'}^{(2)}}{N_{\lambda'}^{(1)}} = \frac{(\epsilon_1/\epsilon_2)^{\lambda/\lambda'}}{\epsilon_1/\epsilon_2} = (\epsilon_1/\epsilon_2)^{\frac{\lambda-\lambda'}{\lambda'}} \qquad (7)$$

Now if r = .02 sterad^{-1} and we change the cavity hole diameter from 2 mm to 4 mm, thereby increasing Ω by a factor of 4, Eq. 5 shows that ε changes from .999 to .996. This would mean at 3250 A using Eq. 7

$$\frac{N_{3250}^{(2)}}{N_{3250}^{(1)}} = \left(\frac{.999}{.996}\right)^{\frac{6500-3250}{3250}} = 1.003$$

and N_{3250} of the gray body would increase by 0.3%. However if r = 0.1 sterad^{-1}, ε would change from .995 to .98 and the change at 3250 A would be 1.5%. Thus by noting the change, one can check the room temperature determination of the partial reflectivity. In the actual experiment one uses tungsten strip lamps as a transfer source at each wavelength. This experiment was performed and within the total precision available (~.3%) the partial reflectivity was confirmed to be 0.02 ±.02 steradians^{-1}. An r = .04 sterad^{-1} represents an emissivity with a 2 mm diameter hole of .9987.

There is one other thing that we have thought of that could effect the quality of our graphite blackbody. The radiation leaving the cavity hole could be partially absorbed by gases in the vicinity of the hole and at a lower temperature than the cavity. The major gases of concern would be C, C_2 and C_3. Other molecules should not be present due to the argon atmosphere, and it was determined from the literature that the concentration of C and C_3 would be a factor of 10 greater than C_2 at 2500 °K and that other species such as C_4 and C_5 would be negligible. For C we could easily determine the presence of the strong 2478 A line by scanning in wavelength with a narrow slit. This was done and we saw nothing, probably part of the reason is that the lower state of this transition is about 21648 cm^{-1} above the ground state thereby not being highly populated at a temperature below 2500 °K. Incidentally, we saw no spectral lines or bands of lines due to CN, C_2 or other molecules. The resonance lines of sodium at 5890, 5896 A and of potassium at 7665 A were weakly visible and the blackbody should not be used near these lines. They are probably a result of impurities in the graphite.

Little is known about C_3 spectra or its energy levels and, unfortunately, there is a broad, largely continuous band in the neighborhood of 4000 A that has been attributed to C_3. Such a band especially if it were present to the extent of 1 or 2% in absorption would not be easily detected. After some thought, the following sensitive technique was evolved for determining the possible presence of the band.

The relative emissivity of a tungsten ribbon, at least over a few hundred angstroms, appears to be well known. For example, the relative emissivity between 4300 A and 4000 A are the same within about .2% whether calculated from DeVos' or Larrabee's values. Therefore, if a strip lamp has the same spectral radiance at 4300 A as a blackbody, the ratio at 4000 A from Eq. 6 is

$$\frac{N_{4000}^{bb}}{N_{4000}^{strip}} = \frac{\left(\tau_{4300}\,\epsilon_{4300}\right)^{4300/4000}}{\tau_{4000}\,\epsilon_{4000}} \qquad (8)$$

and can be calculated to about .2%. This calculation was performed and the ratio was also determined, experimentally. The agreement was well within the total calculated and experimental error (~.3%). Thus it is unlikely that C_3 absorption at 4000 A is a significant factor in effecting the blackbody quality.

This technique can also be used to determine how close to the impurity spectral lines one can use the blackbody.

As a result of the various calculations and experimental measurements described, it is believed that the graphite high temperature blackbody satisfied our initial requirements.

BLACKBODY TEMPERATURE MEASUREMENT

The uncertainty of visual optical pyrometer calibrations at 2500 °K are at best about 5 deg relative to the International Practical Temperature Scale (IPTS). Recently, the accuracy of realizing the IPTS has been significantly improved at NBS using a specially designed photoelectric pyrometer. This pyrometer has been calibrated on the IPTS at 2500 °K with an uncertainty (95% confidence) of about 1.0 deg. In correcting to the Thermodynamic Kelvin Temperature Scale (TKTS) the total resulting uncertainty (95% confidence) is about 2.4 deg. However, this additional uncertainty is expected to be virtually eliminated in a few years because of a significantly more accurate (~.05 degrees) determination at NBS of the freezing temperature of gold on the TKTS. Nevertheless, at present the uncertainty of a temperature measurement on the IPTS and TKTS at 2500 °K is about 4 and 10 times our criterion, but there are high expectations of the correction to the TKTS introducing insignificant additional uncertainty in a few years. Our plan then, as is common in temperature standards, is to work on the IPTS and correct to the TKTS when desirable with the best corrections then available.

Since the blackbody temperature measurement is the major limitation discussed, we decided to

(1) Make the photoelectric pyrometer a part of the spectroradiometer utilizing similar optics, detectors, target areas, etc. The thought was that this would minimize any errors in transferring the temperature scale to the blackbody.

(2) Calibrate the pyrometer portion of the spectroradiometer from basic principles, i. e. a primary calibration.

Fig. 2 shows a block diagram of the spectroradiometer that has been developed. At 6545.7 A it is used as a photoelectric pyrometer. A tungsten vacuum strip lamp, selected for maximum stability, is used as the equivalent of the small lamp in an ordinary pyrometer. Absorbing glasses are used for temperatures above about 1320 °C as in an ordinary pyrometer. The pyrometer lamp is compared to the blackbody by alternately positioning the two sources on the entrance slit of the monochromator. In front of the entrance slit is one of two metal slit masks, limiting the slit height to either 0.2 mm or 0.8 mm. The masks are engraved with two perpendicular scales having 0.1 mm divisions. This facilitates precise positioning of the sources. With the aid of the slit telescope it is possible to do this to about 0.02 mm. Such precise positioning is necessary with some lamps. The vacuum strip lamp and other sources are placed in double gimble mounts which provide six degrees of freedom with micrometer type motion. This makes possible the investigation of the effects of changing orientation or position of the sources with a resolution of about 0.05% in spectral radiance.

The electronics indicated in Fig. 2 is that with which, through pyrometry, we have had considerable success in high precision (~.02%) low level measurements ($<10^{-8}$ amp). The radiation is not chopped and a D.C. amplifier is used. With the biasing system used, 0.1 inch on a recorder chart is equivalent to 0.2% spectral radiance. The signal to noise ratio varies depending on the temperature, but in the worse case we are able by integrating over one or two inches on the recorder chart to obtain a precision in terms of a standard deviation of 0.05% when comparing two vacuum lamps or a lamp and a blackbody. Since the two radiations are adjusted to be almost identical, i.e., we have essentially a null type instrument, no errors arise due to non-linearity of the photomultiplier or electronics. The photomultiplier has an

S20 response and a quartz window. When it is used at a current level of about 10^{-8} amperes and is in operation for about 45 minutes, the fatigue produces a very small linear change which has a negligible effect on our measurements ($<.05\%$).

In order to calibrate the pyrometer portion of the spectroradiometer from basic principles, it is necessary to start with the definition of the IPTS above 1063 °C. This part of the IPTS is defined in terms of the ratio of two blackbody radiances, one being at the temperature of equilibrium between liquid and solid gold (gold point). Mathematically,

$$\frac{N_{b\lambda}(t)}{N_{b\lambda}(t_{Au})} = \frac{e^{C_2/\lambda(t_{Au}+T_0)} - 1}{e^{C_2/\lambda(t+T_0)} - 1} = R \tag{9}$$

where t_{Au} = 1063 °C, To = 273.15 deg and C_2 = 1.438 cm deg.

The initial requirement in a primary calibration is the gold point blackbody. The one we used is shown in Fig. 3. It has been thoroughly checked with the NBS photoelectric pyrometer and all tests and calculations confirm that the emitted radiation in the vicinity of 6545 A is within .01% of that from a perfect blackbody at the temperature of freezing gold.

The wavelength in Eq. (9) is required to be known to at least 2.5 A if 0.12 deg ($\sim$0.1% in N_λ) accuracy is desired at 1320 °C. From the theory of optical pyrometry, the wavelength in Eq. (9) is the mean effective wavelength between temperatures t_{Au} and t, $\lambda_{t_{Au}-t}$ where

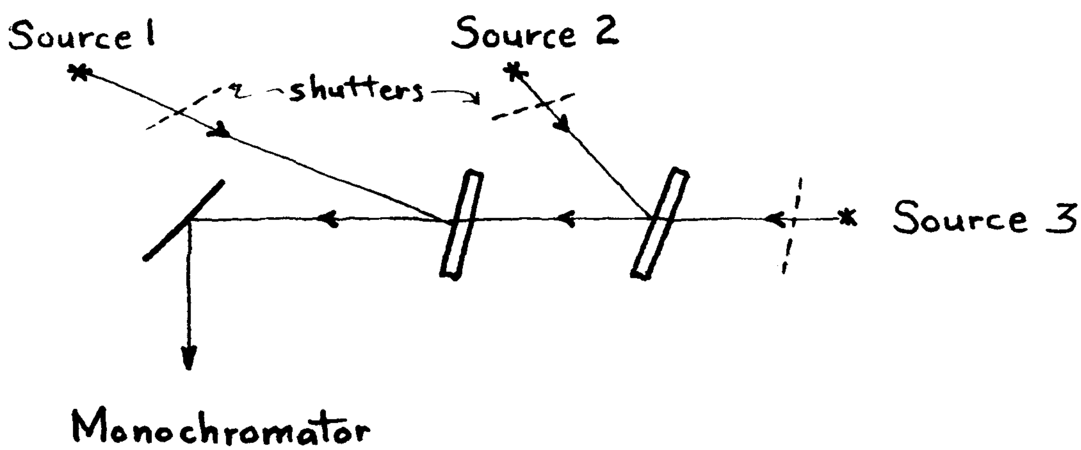
$$\frac{1}{\lambda_{t_{Au}-t}} \cong \frac{1}{2}\left(\frac{1}{\lambda_t} + \frac{1}{\lambda_{t_{Au}}}\right) \tag{10}$$

and

$$\frac{1}{\lambda_t} = \frac{\int_0^{\infty} \frac{N_{b\lambda}(t)\, \sigma(\lambda_o \lambda)\, \mathcal{R}(\lambda)}{\lambda}\, d\lambda}{\int_0^{\infty} N_{b\lambda}(t)\, \sigma(\lambda_o \lambda)\, \mathcal{R}(\lambda)\, d\lambda} \tag{11}$$

where λ_t is the effective wavelength at temperature t. The slit or apparatus function is $\sigma\ (\lambda_o \lambda)$ and $\mathcal{R}(\lambda)$ is the spectral response of the entire system. All these functions were carefully determined, and calculations showed when a 0.6 mm slit width (~24 A width) was used, the mean effective λ was shifted from the λ setting of the monochromator when using a narrow slit and spectral line by about 0.1 A with an uncertainty of about 0.5 A. It was quite adequate, therefore, to use the wavelength corresponding to the peak of a narrow spectral line determined with a narrow slit when realizing the low range of the IPTS. The maximum uncertainty due to mean effective wavelength in the calibration is estimated to be about 0.03 deg.

The ratio of spectral radiance, $\mathcal{R}$, in Eq. (9) was obtained with the beam conjoiner shown below.



By adjusting each source in the conjoiner to independently match the gold point blackbody, all three sources together would represent an $\mathcal{R}$ of 3. By adjusting two sources to be equal to each other and together equal to three times the gold point, each will represent an $\mathcal{R} = 3/2$. In this manner, many different integral and fractional values of R can be obtained without any assumption of linearity of the photomultiplier or electronic system. There is one assumption required however, and this has been tested experimentally. It is that the relative response of the photomultiplier over the bandwidth of the monochromator does not depend on the magnitude of the spectral radiance.

Using the beam conjoiner, ratios of about 3/4, 1, 3/2, 2, 3, 4, 6, 8, 12, and 14 and the corresponding currents for the pyrometer reference lamp (A9) were obtained. Using these $\mathcal{R}$'s and the correct mean effective wavelength, Eq. (9) was used to determine the corresponding blackbody temperatures. A fourth order equation of current as a function of temperature was then fitted by a least squares criterion to the resulting ten temperatures and corresponding currents. The standard deviation of the fit was about .05°.

Two low range calibrations were performed, the second 260 hours of lamp burning time after the first. The two low range calibrations differed by a constant of 0.83° with a standard deviation of the difference of the unfitted data of .061 °C. This corresponds to a standard deviation of one low range calibration of .043 °C. Incidentally, the drift of lamp A9 is now, after about 400 hours of use, 0.001° per hour.

One correction, that has not yet been mentioned, had to be applied. This was the effect of scattered radiation when comparing a large source such as the gold point blackbody to a smaller source such as a vacuum strip lamp. This effect was determined by performing the complimentary experiment.

A hole in a white illuminated diffuse surface was imaged on the slit of the spectroradiometer. For any particular condition of the entrance optics, the radiation detected depends on the size and shape of the illuminated surface. This could easily be changed by placing black velvet or "flock" paper of various shapes in front of the illuminated surface. The correction varied from about .1% to .3% in radiation depending on the age of the coating on the first two mirrors and their cleanliness.

The upper ranges of the pyrometer were calibrated by determining transmittances for the individual absorbing glasses using the low range calibration. This was accomplished by matching a vacuum lamp near 1320 °C, observed through an absorbing glass, with a vacuum lamp near 1040 °C observed directly, so that

$$\tau(\lambda)\, N_{b\lambda}(T_{High}) = N_{b\lambda}(T_{Low}) \tag{12}$$

Using Wien's equation which has an error of only about 0.0001% for the maximum value of λT used in the low range, one obtains

$$\tau(\lambda) = e^{-\frac{c_2}{\lambda}\left(\frac{1}{T_L} - \frac{1}{T_H}\right)} = e^{-c_2 A/\lambda} \tag{13}$$

where A is the so-called "A" value of the absorbing glass.

In pyrometry, absorbing glasses are usually selected which have an exponential transmittance, i.e.

$$\tau(\lambda) = e^{-K/\lambda} \tag{14}$$

In this case, the "A" value is independent of the mean effective wavelength and need only be determined with two temperatures such as in Eq. (13). Also from Eq. (13) two or three filters can be used in series; and, neglecting reflection, the resulting "A" value is the sum of the individual "A" values.

Using the above principles and correcting for reflectances, which were experimentally determined (~.16% correction for two absorbing glasses), the "A" values were obtained for groups of one, two and three absorbing glasses, and the higher range calibrations consisting of these "A" values and the low range calibration were thus obtained.

One additional point; the glass usually used in pyrometers for absorbing glasses is Corning Pyrometer Brown. This glass was found to have a temperature coefficient, transmittance decreasing with an increase in glass temperature, that made it difficult to use with the precision desired. Another glass was found however, Jena NG-3, which also had an exponential transmittance but had a coefficient with the opposite sign. The two glasses were combined in a composite filter with their thicknesses selected so that the temperature coefficient was negligible.

The pyrometer portion of the spectroradiometer has been calibrated with an estimated uncertainty of about 1 deg at 2500 °K on the IPTS, the same as that possible with the NBS photoelectric pyrometer. We thus missed our initial objective of 0.24 deg (~.1% in N_{5500}) by a factor of four.

COMPARISON OF BLACKBODY AND TUNGSTEN STRIP LAMP

Many of the features required for using the spectroradiometer as an accurate pyrometer at 6545.7 A are obviously equally useful at other wavelengths where the high temperature blackbody and a gas tungsten strip lamp are compared. The wavelength accuracy and scattered light (or slit function wings) are not quite as serious since a wavelength accuracy of about 5 A corresponds to a matching error in the visible of only 0.1%. The major new factor is the gas lamp itself.

The best gas lamps we have observed drift about 0.002% per hour at a 2500 °K brightness temperature in the red and about .01% per hour for 2625 °K. However, some lamps have been observed to drift by a factor of 100 greater. Thus only the best lamps available are stable enough not to limit the accuracy of the calibration. Even then their burning time should be kept to a minimum.

The gas lamp normally used in our calibrations is the GE 30A/T24/3. It has a quartz window, a 3 mm x 44 mm filament, and has a small notch in the filament opposite the window. We prefer them over the newer shorter filament GE lamps because of the smaller temperature gradient, over the viewing area of about .6 mm x .8 mm.

Before calibration, the optimum orientation for the lamp is determined. The radiation from the target area is very noisy and even oscillatory unless the lamp filament is oriented close to vertical. This is believed to be caused by convection effects of the argon gas around the hot filament. When the most favorable orientation is determined an arrow is etched on the back surface of the lamp and a line through the center of the notch and tip of the arrow serves as a reference axis. This axis is usually made horizontal and is also approximately the optic axis of the spectroradiometer, thereby insuring not only a reproducible orientation but also a reproducible direction of sighting on the lamp.

The extent to which the lamp is polarized when oriented and viewed as described above is determined at about 5000 A where the spectroradiometer is depolarized. The instrument is depolarized with two plates of calcium fluoride properly oriented and placed between the exit slit and the detector.

Usually the polarization of a lamp is less than 1%.

The reproducibility of the blackbody and gas tungsten strip lamp comparison, using the lamp and blackbody as described, has a standard deviation ranging from about .05% at 6500 Å to .15% at 3000 Å and .3% at 2100 Å.

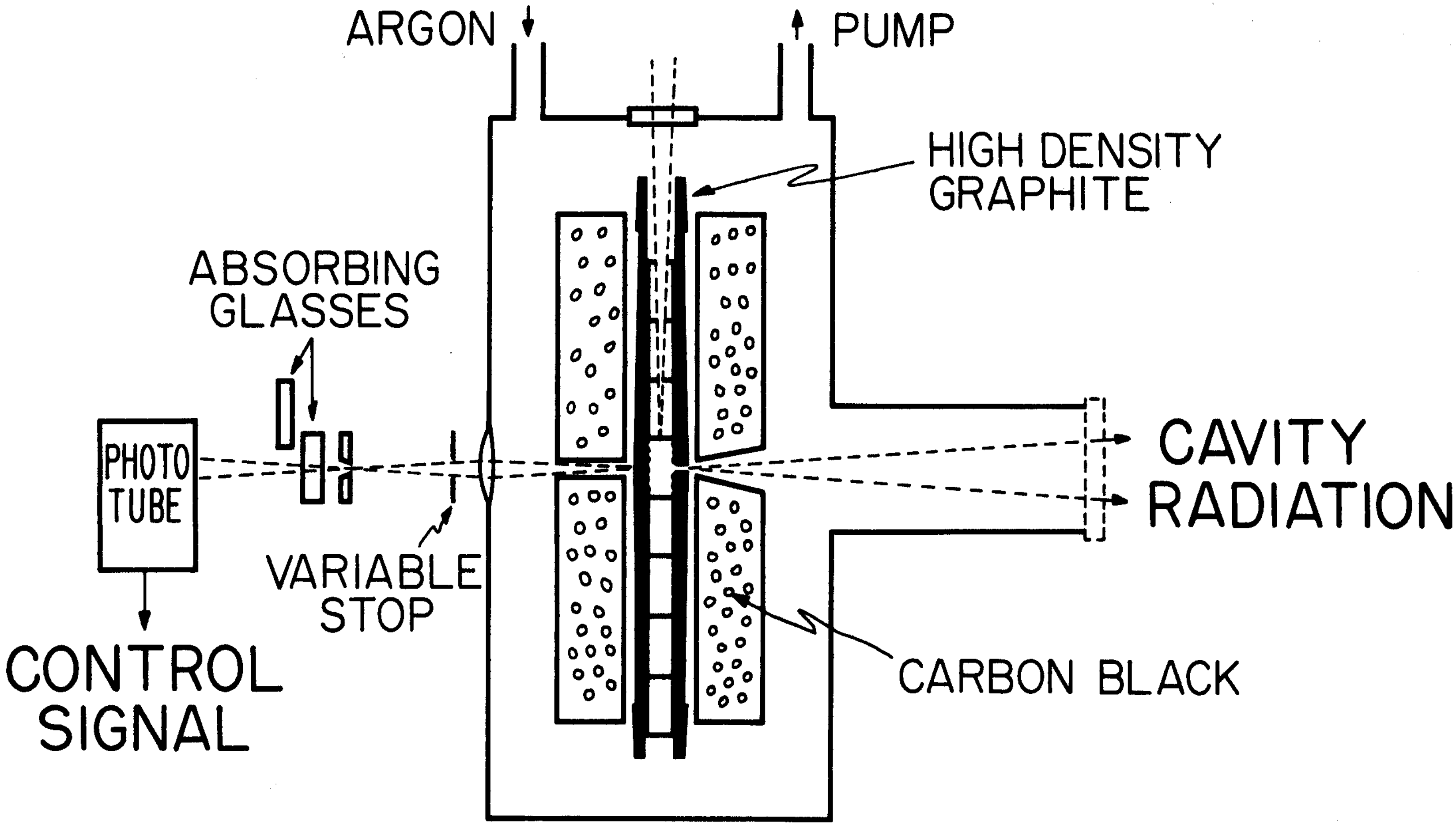
SUMMARY OF RESULTS

The table below summarizes the estimated uncertainty in terms of spectral radiance with which the spectro-radiometer has been calibrated. The uncertainties are broken down into that due to the blackbody and that due to the temperature measurement and are given in terms of a standard deviation, σ. The total uncertainties, however, are twice the square root of the sum of the squares of the individual uncertainties, corresponding to a 95% confidence limit.

		2100 A	3000 A	6500 A
Blackbody Uncertainty σ		0.4%	0.25%	0%
Temperature Uncertainty (σ)	IPTS	.95	.65	.3
	TKTS	.95	.65	.3
Total Uncertainty (2σ)	IPTS	2.1	1.4	.6
	TKTS	2.8	1.9	.85

The transfer of the spectroradiometer calibration on to a stable unpolarized tungsten strip lamp can be accomplished with negligible additional uncertainty.

The results of a calibration are usually reported in terms of the International Practical Temperature Scale. This is done because the IPTS is more convenient to realize and more precise than the TKTS. When necessary a correction can be made to the TKTS. The additional uncertainty in spectral radiance resulting from the correction to the TKTS is expected to decrease significantly in a few years.



GRAPHITE BLACKBODY

Fig. 1

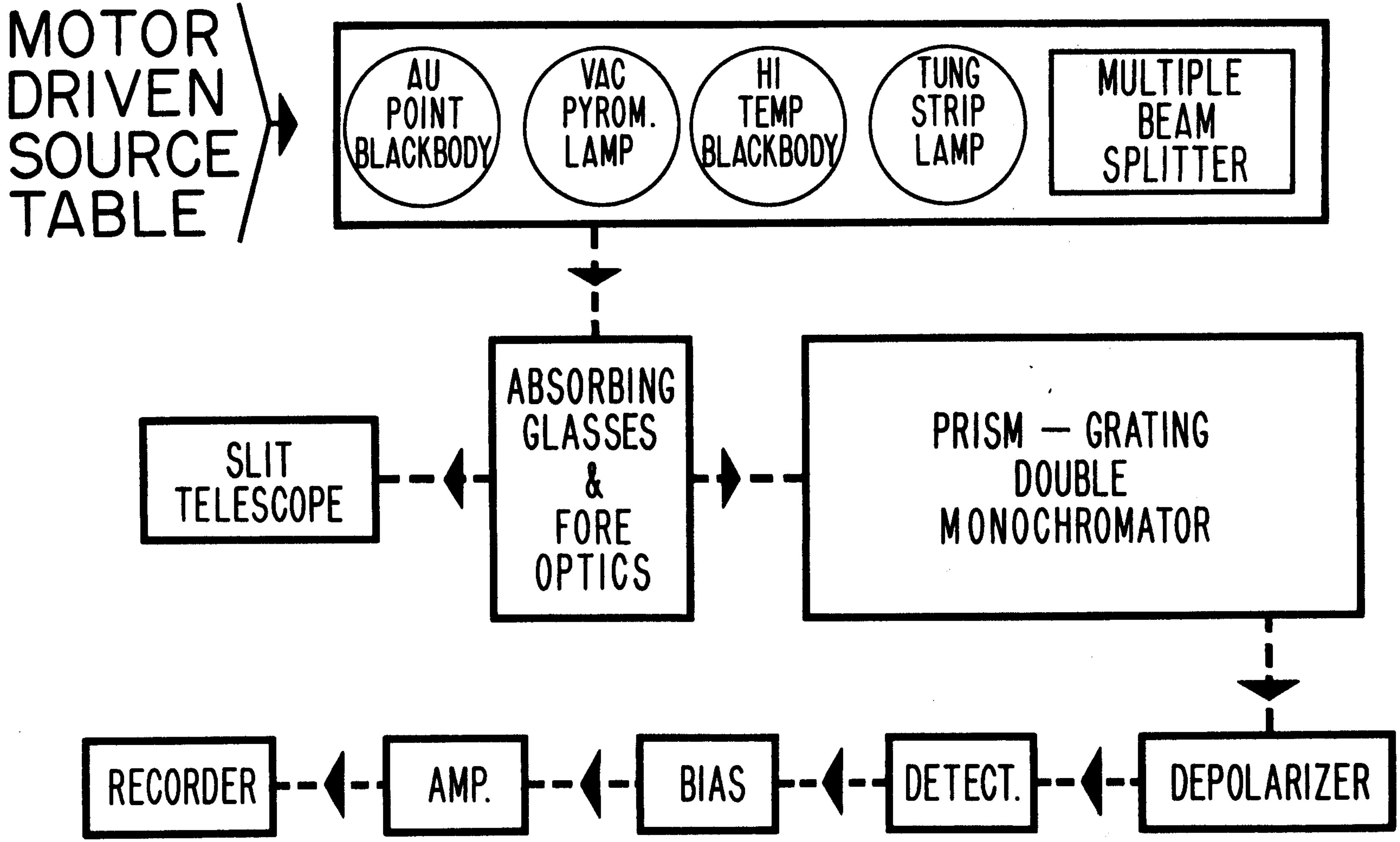


Fig. 2

High Accuracy Spectroradiometer

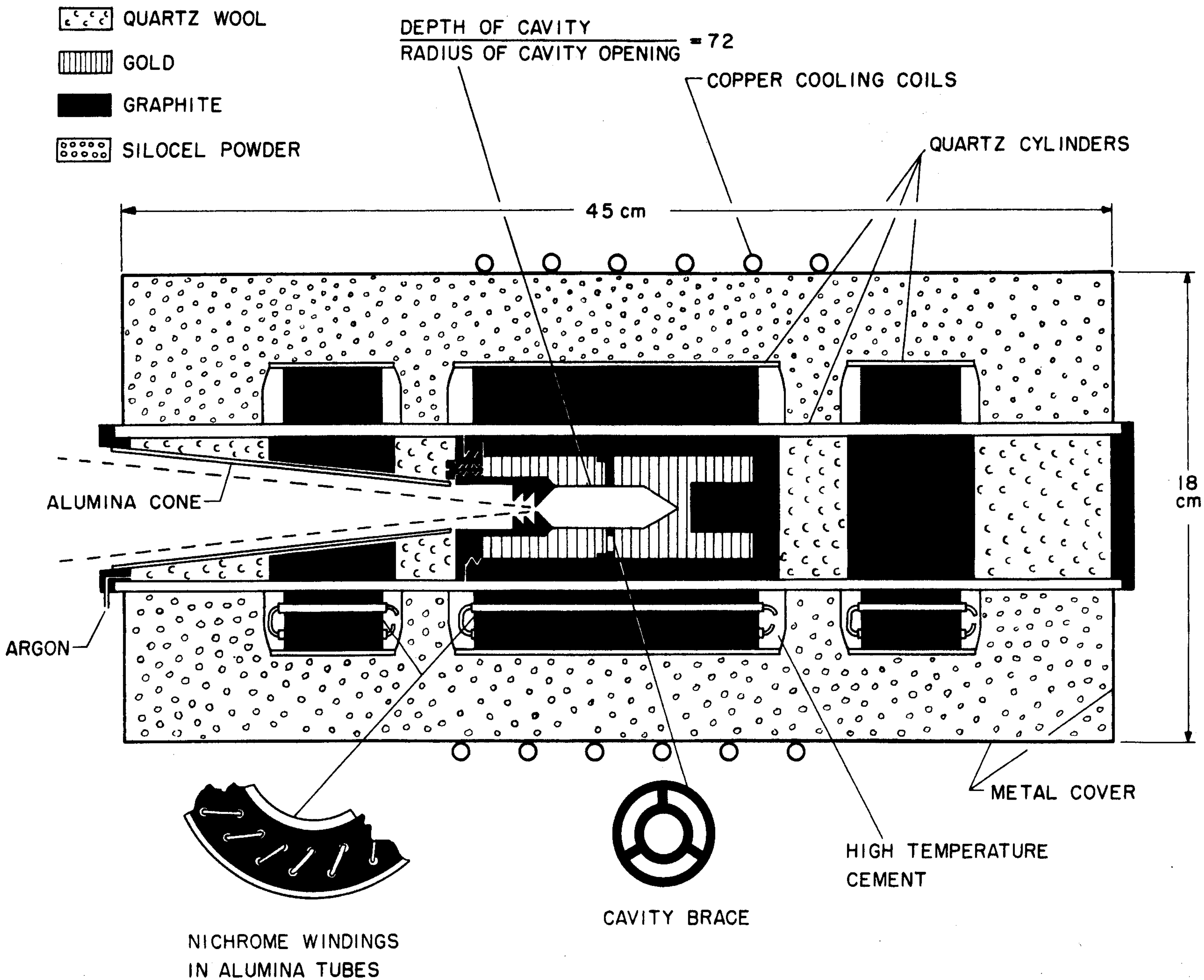


Fig. 3 Gold-point Blackbody

PART III

SPECTRAL RADIANCE OF THE LOW CURRENT GRAPHITE ARC

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SPECTRAL RADIANCE OF THE LOW CURRENT GRAPHITE ARC

A. T. Hattenburg and H. J. Kostkowski

Introduction

The low current graphite arc has long been of interest as a bright, reproducible source of radiation. A number of workers [1-6] have investigated the spectral radiance of this source using graphite and/or carbon (lampblack base) electrodes and employing various calibration techniques to yield absolute values. Nevertheless, at 4000 Å differences between two of the more widely used results [4,5] are as high as 15%, and below 4000 Å there have been fewer investigations and the uncertainties are greater. The development of a high accuracy spectroradiometer, which is described elsewhere in this report, made possible a more accurate determination of the arc spectral radiance from 8500 Å to 2100 Å. This part of the report presents the results of this determination.

Method

The normal use of the spectroradiometer involves comparing the source to be calibrated to a high temperature blackbody, which is adjusted to be equal to the source at each desired wavelength. A modification of this procedure was necessary in the case of the graphite arc, since its spectral radiance exceeded that of the blackbody by a factor as large as 4400 in the short wavelength region.

Two possible methods of comparing these unequal sources were considered. The first method involved using a filter to reduce the spectral radiance of the arc to that of the blackbody, and then using the spectroradiometer in its usual null mode. This required an accurate determination of the filter transmittance at each wavelength of interest.

Though laborious and time consuming, this method should be capable of an accuracy approaching that available in the normal method of using the spectroradiometer. In the second method, the ratio of spectral radiance of the blackbody and arc would be obtained from the ratio of the electrical currents of the photomultiplier tube corresponding to the two radiation signals, after being amplified and presented on the recorder. This second scheme would facilitate the collection of data, but introduced a new source of error, the possible departure from linearity of the photomultiplier and the associated amplifier.

In choosing between the two methods of calibration, the reproducibility of the graphite arc became the deciding factor. Careful measurement of arc stability indicated a variation in arc radiance corresponding to a standard deviation of about 1% to 2% at 6500 to 2500 Å, respectively, about 3 times the corresponding uncertainties for the spectroradiometer. Also, preliminary tests indicated that the error due to departure from linearity could be largely corrected and would not add significantly to these uncertainties. Therefore, the second and easier of the two methods outlined above was chosen.

<u>Arc</u>

The arc employed was a commercial device manufactured by the Mole-Richardson Company, and designated as the Pyrometric Molarc Lamp type 2371. It was operated in a manner recommended by the manufacturer. It employs a rate adjustable continuous feed mechanism for both electrodes as well as the necessary manual adjustments, a 120° angle between electrodes, and an imaging screen to make possible continuous monitoring of the electrodes positions. The arc power supply consisted of a 120 volt battery, a suitable resistor for ballast and a carbon pile rheostat for fine current adjustment.

The negative electrodes were National Carbon AGKS graphite, 1/8" diameter, and the anodes were National Carbon SPK graphite, 1/4" diameter. The anode was burned for at least ten minutes before any data was taken. The arc was operated at a current approximately 1/4 ampere below the overload point. This proximity to overload was checked before each reading, and no readings were taken until one minute after the hissing stopped. The electrode spacing was constantly monitored to maintain the anode face in the plane normal to the anode axis, and focused on the slit of the monochromator. The target area observed was 0.1 mm wide and 0.8 mm high centered on the anode.

Experimental Procedure

The spectral radiance of the anode, as viewed through the arc stream, was determined at a number of selected wavelengths from 8500 to 2100 Å. The measurements were made at fixed wavelengths, rather than by continuous scans, so that the current of the arc could be maintained at the proper value below the overload point, and short term variations and noise in the arc signal could be averaged for each wavelength. The wavelengths longer than 2700 Å were selected on the basis of a small radiance contribution from the arc stream and therefore from line or band spectra. At wavelengths shorter than 2700 Å, where the arc stream contributed significantly at all wavelengths, the measurements were made every 100 Å.

In order to determine the desired wavelengths above 2700 Å, continuous scans from 2700 Å to 8500 Å were made of the arc stream alone with a spectral slit width of 0.2 Å. The arc stream was observed from the side, at a point about 0.5 mm in front of the anode. These measurements were supplemented by viewing the stream section between anode and cathode from the front, with the arc tilted about 15° (causing the anode to face downward).

For the spectral radiance determinations, the blackbody was set at a high temperature (~2850°K), and this temperature measured before and after each set of measurements. The arc was compared to the blackbody at each chosen wavelength by alternately centering the images of the two sources on the monochromator slit, and selecting the required amplifier gain. The resulting pen deflections and corresponding amplifier gains yielded the desired ratio of spectral radiance. The spectral band pass was 2.4 and 4 Å at the short and long wavelengths respectively, while the aperture was about f/12.

The departure from linearity of the detector-amplifier response was determined at two wavelengths, using the blackbody to obtain the required radiance ratios at a short wavelength (3400 Å) and the calibrated filters (absorbing glasses) of the spectroradiometer at a long wavelength (6546 Å). The observed departure from linearity did not depend on wavelength and varied from about 1/2% at the lower ratios to 4% for those at about 4400.

Results

The spectral radiance of the graphite arc, relative to a 3800 °K (IPTS) blackbody, has the general appearance shown in Fig. 1. The large deviations from a ratio of one which occur in the middle wavelength regions are caused by CN and C_2 molecular band spectra, and are highly discrete in character. The departure below 2600 Å is largely continuous.

The results for the selected wavelengths are given in Fig. 2. The mean spectral radiance for a group of six graphite anodes are shown relative to a 3800 °K (IPTS) blackbody. Each point includes data from about four anodes. The bars shown for a few of the points represent plus and minus the sample standard deviation about the sample mean. The measurements on the arc stream alone permitted an interpolation and extrapolation for some of the points in Fig. 2. These results are given in Table I. The spectral radiance of the arc (anode and arc stream) throughout each of the listed spectral regions is equivalent to a blackbody with the temperature given in Table I. From 2600 Å to 2100 Å, the arc stream contribution

TABLE I. Blackbody or Radiance Temperatures of Arc

Wavelength (Å)	Blackbody Temperature (°K IPTS)
8500 - 5640	3795 °K
5360 - 5175	3795
4875 - 4755	3795
4350 - 4220	3800
3975 - 3950	3820
3650 - 3640	3818
3300 - 2800	3806
2600	3828
2500	3851
2400	3895
2300	4076
2200	4175
2100	4342

becomes increasingly large relative to the anode crater radiation, exceeding it below 2300 Å. The resulting arc radiation is not represented by any one blackbody curve. Therefore in Table 1, only specific wavelengths are listed for this region.

The arc spectral radiance can be obtained from the IPTS blackbody temperatures in Table 1 by using the following equation:

$$N_\lambda = \left[1.191\,\lambda^{-5}\Big/\left(e^{\frac{C_2(\mathrm{IPTS})}{\lambda T(\mathrm{IPTS})}} - 1\right)\right] e^{\frac{1}{\lambda}\left[\frac{C_2(\mathrm{IPTS})}{T_{Au}(\mathrm{IPTS})} - \frac{C_2}{T_{Au}}\right]}$$

Since C_2(IPTS) = 1.438 cm deg, T_{Au}(IPTS) = 1336.15°K and using the "best" values for C_2 and T_{Au} where C_2 = 1.43879 cm deg and T_{Au} = 1337.65°K

$$N_\lambda = \left[1.191\,\lambda^{-5}/\left(e^{\frac{1.438}{\lambda T(\mathrm{IPTS})}}-1\right)\right]\left[1 + \frac{0.00616\times 10^{-4}}{\lambda}\right]$$

where the wavelength λ is in centimeters and N_λ is in watts (steradian)$^{-1}$ (cm)$^{-3}$. The factor in parenthesis represents the correction due to converting from the International Practical Temperature Scale (IPTS) to the Thermodynamic Kelvin Temperature Scale (TKTS). Because of the relative ease of realizing and maintaining the IPTS and its international acceptance, temperatures are normally measured and reported on this scale. Nevertheless, when using a temperature to calculate another physical parameter in an equation from thermodynamics or statistical mechanics, it is necessary, for the most accurate result, to convert to the Thermodynamic Kelvin Temperature Scale.

The results in Table 1 were obtained under specific conditions of f/number, spectral band pass and target area. If different conditions are used, experimental checks should be made of the effect of these changes on the results. Some of these checks are being performed and will be reported in the current work when it is published. Use of an arc other than the Molarc lamp used here may also alter the results, particularly below 2800 Å.

Uncertainty of Results

The uncertainties in the spectral radiance are due primarily to the variations in the arc itself, the response characteristic of the photomultiplier-electronics system, the calibration of the spectroradiometer, and the uncertainty of the Thermodynamic Kelvin Temperature Scale (TKTS).

The arc variations are reflected in the standard deviations of the individual measurements, and vary from about 1% to 2% from 8500 Å to 2100 Å. The calibration of system response is uncertain to about 1/2% for values down to 2400 Å, and somewhat greater at shorter wavelengths, about 3% at 2100 Å. The spectroradiometer has an uncertainty in terms of a standard deviation of about 0.4% at 8500 Å and 1.1% at 2100 Å relative to the IPTS. Finally, conversion to the TKTS adds an uncertainty of about 0.25% at 8500 Å and 1% at 2100 Å. Combining these results in quadrature results in a standard deviation uncertainty of 1.2% at 8500 Å, 2.4% at 2400 Å, and 3.9% at 2100 Å, or a 95% confidence limit uncertainty of 2.4% at 8500 Å, 4.8% at 2400 Å and 7.8% at 2100 Å.

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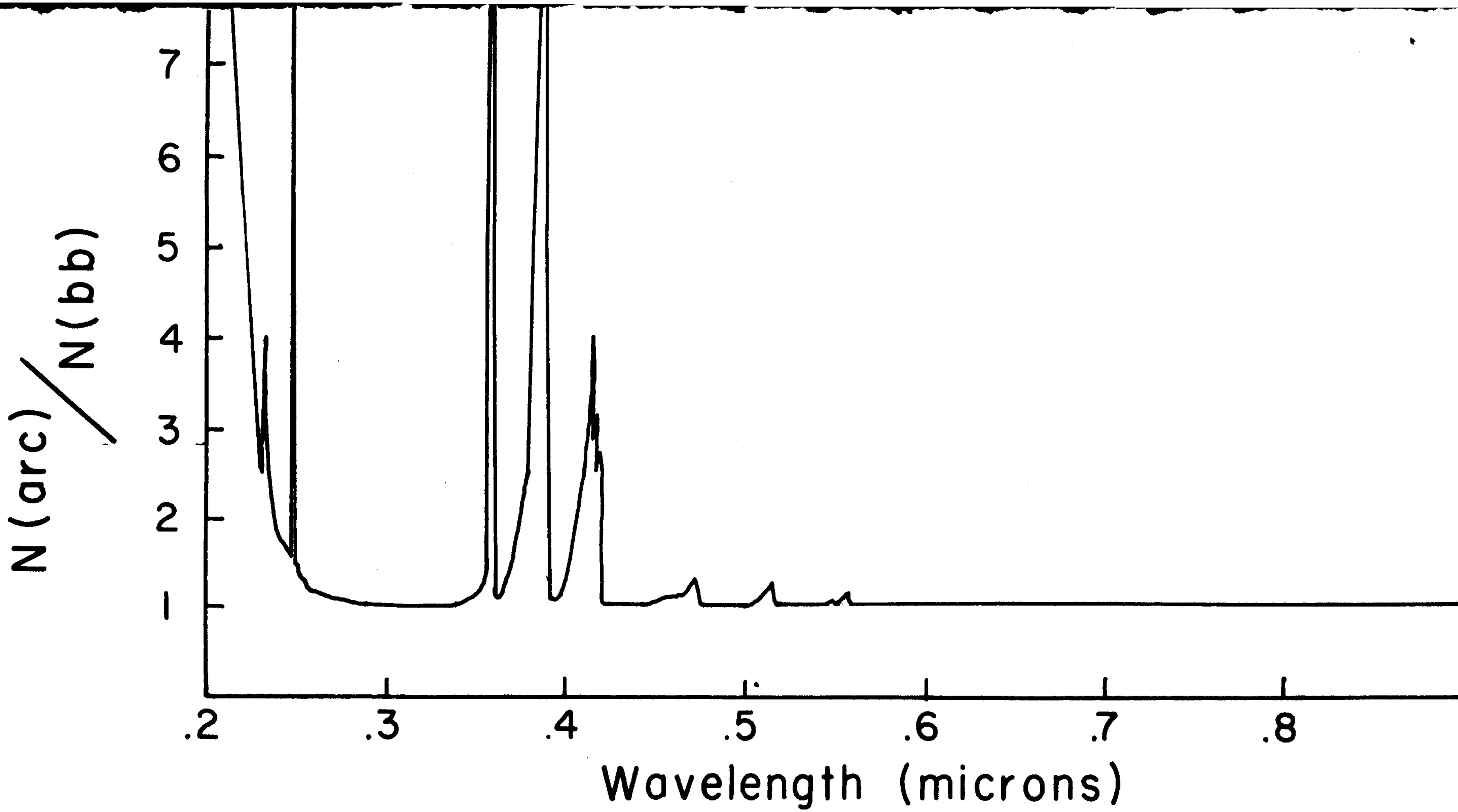
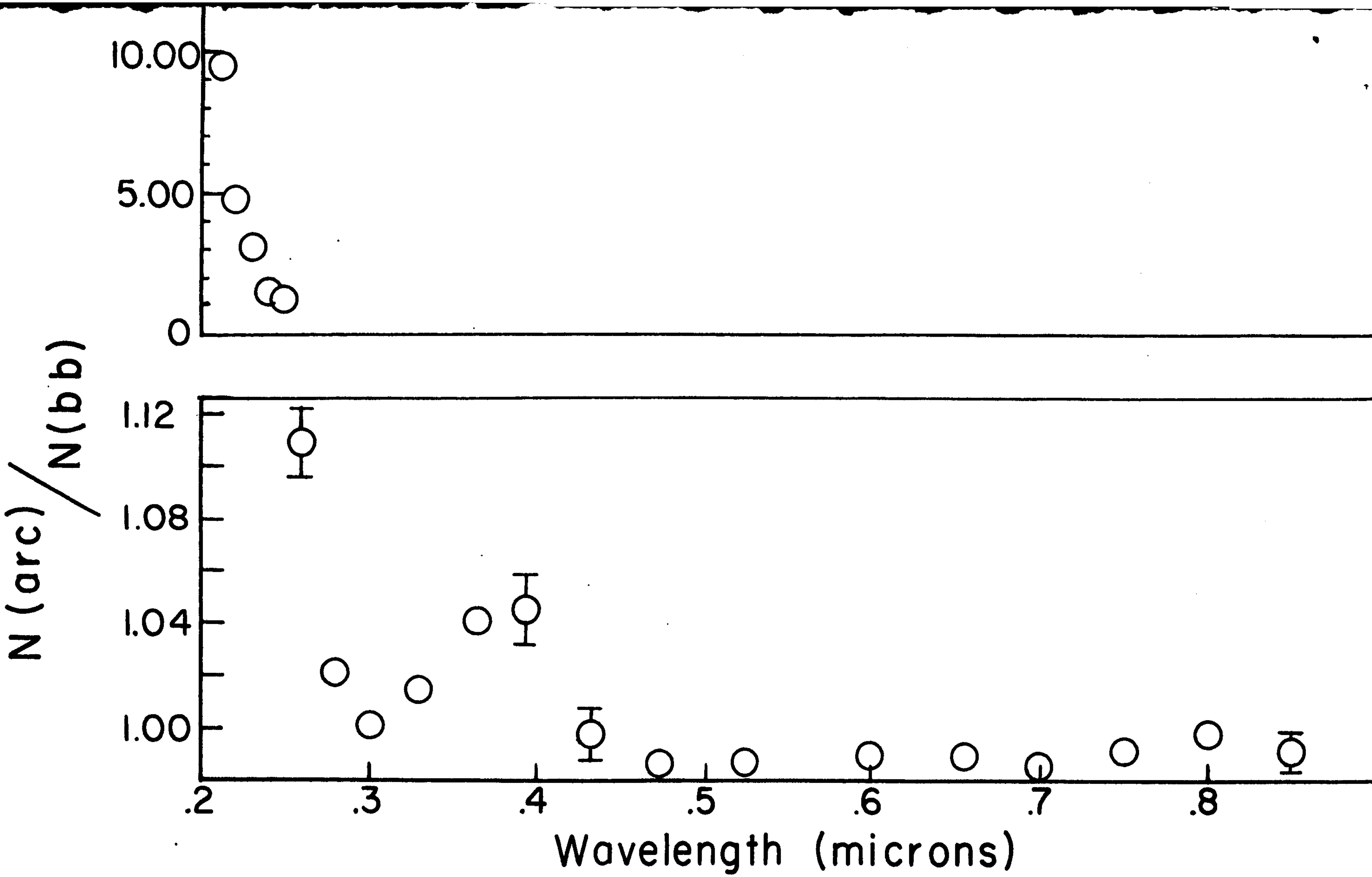


SPECTRAL RADIANCE OF GRAPHITE ARC
RELATIVE TO 3800 °K(IPTS) BLACKBODY

Fig. 1



SPECTRAL RADIANCE OF GRAPHITE ARC RELATIVE TO 3800 °K(IPTS) BLACKBODY

Fig. 2